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A Visual Guide to the Universe

Course Guidebook

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PUBLISHED BY:

THE GREAT COURSES
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Chantilly, Virginia 20151-2299
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Printed in the United States of America

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Professor David M. Meyer is Professor of Physics and Astronomy and Director of the Dearborn Observatory in the Center for Interdisciplinary Exploration and Research in Astrophysics at Northwestern University. He received his B.S. in Astrophysics at the University of Wisconsin–Madison after completing a senior honors thesis on ultraviolet interstellar extinction with Professor Blair Savage. Professor Meyer earned his M.A. and Ph.D. in Astronomy at the University of California, Los Angeles, working with Professor Michael Jura on measurements of the cosmic microwave background radiation from observations of interstellar cyanogen. He then continued his studies as a Robert R. McCormick Postdoctoral Fellow at the University of Chicago's Enrico Fermi Institute before joining the Northwestern faculty in 1987.

Professor Meyer's research focuses on the application of sensitive spectroscopic techniques to astrophysical problems involving interstellar and extragalactic gas clouds. Utilizing a variety of ground- and space-based telescopes, he studies the optical and ultraviolet spectra of stars and quasars to better understand the composition, structure, and physical conditions of intervening clouds in the Milky Way and other galaxies. Over the past 25 years, much of his research has involved space telescopes in general and the Hubble Space Telescope in particular. During this time, Professor Meyer and his collaborators have been awarded more than $2 million in NASA research funding to carry out space observations that have resulted in 32 peer-reviewed publications on topics ranging from the abundance of interstellar oxygen to the gaseous character of distant galaxies. Professor Meyer also has served five times on the committee that annually selects the most deserving proposals for Hubble observing time.

During his career at Northwestern, Professor Meyer has specialized in designing and teaching introductory undergraduate courses in astronomy, cosmology, and astrobiology for nonscience majors. A hallmark of his lectures is the use of Hubble images to bring the latest research into the introductory classroom. His success in such efforts has led to a number of teaching awards, including Northwestern's highest teaching honor, the Charles Deering McCormick Professorship of Teaching Excellence. His other honors include the Martin J. and Patricia Koldyke Outstanding Teaching Professorship, the Weinberg College Distinguished Teaching Award, and the Northwestern University Alumni Excellence in Teaching Award.

Professor Meyer's previous Great Course is entitled *Experiencing Hubble: Understanding the Greatest Images of the Universe*. ■

About our Partner

Founded in 1846, the Smithsonian Institution is the world's largest museum and research complex, consisting of 19 museums and galleries, the National Zoological Park, and 9 research facilities. The total number of artifacts, works of art, and specimens in the Smithsonian's collections is estimated at 137 million. These collections represent America's rich heritage, art from across the globe, and the immense diversity of the natural and cultural world.

In support of its mission—the increase and diffusion of knowledge—the Smithsonian focuses on four Grand Challenges that describe its areas of study, collaboration, and exhibition: Unlocking the Mysteries of the Universe, Understanding and Sustaining a Biodiverse Planet, Valuing World Cultures, and Understanding the American Experience. The Smithsonian's partnership with The Great Courses is an opportunity to encourage continuous exploration by learners of all ages across these areas of study.

This course, *A Visual Guide to the Universe*, takes you on an enhanced tour of the most interesting places in the universe, using images produced by large space observatories, planetary probes, and a new generation of massive ground-based telescopes. Destinations include the Martian surface, the rings of Saturn, the star-forming Orion Nebula, and the massive black hole in the center of the Milky Way.

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A Visual Guide to the Universe

Scope:

The tremendous growth in our understanding of the universe over the past 50 years is due in large part to the pioneering views provided by a fleet of space probes and space observatories. We live in an age of amazing space discoveries where planets and moons are being seen up close for the first time and the cosmos is being imaged in ways that are not possible from the Earth's surface. Through the eyes of robotic rovers on the surface of Mars, we have learned that the Red Planet may have once been like Earth. Infrared space telescopes have peered inside the optically dark dust clouds of our Milky Way Galaxy and have directly observed star formation in action. The optical acuity of the Hubble Space Telescope has made it possible to image the evolution of distant galaxies in unprecedented detail and map the gravitational signature of the invisible dark matter that dominates the universe.

In this introductory course, we discuss the scientific stories behind some of the most spectacular space images obtained during the past 20 years. Through these images, we tour a variety of the most fascinating places in the solar system, our Milky Way Galaxy, and the greater universe beyond. We also explore in detail the space probes and telescopes themselves in the context of their design, operation, and special imaging capabilities. The lectures are organized to address the topical images from near to far in space and time, beginning with the Sun and ending with the big bang. The image highlighting each lecture is discussed in terms of its topical implications and the broader astrophysical context. A key emphasis throughout the course is how these images have made it possible to visualize and map a universe that is mostly invisible to the Earth-bound human eye.

The course begins with an overview lecture on the expanding frontier of space astronomy. It focuses on the motivations and limitations pushing the robotic exploration of the solar system and the atmospheric constraints driving the deployment of space telescopes to view the universe across the electromagnetic spectrum. The first stop on our solar system tour is the

Sun, as seen through the X-ray and ultraviolet eyes of the Solar Dynamics Observatory. At these wavelengths, it is possible to view in detail the powerful magnetic fields, producing solar flares and coronal mass ejections, that can impact the Earth. We then voyage to the surface of Mars, as seen from rovers at ground level and orbiters imaging from above. This detailed view makes it clear that Mars has evolved from a warm planet with liquid water and a sunstantial atmosphere to a cold, dry, nearly airless desert today. Beyond the orbit of Mars, we explore the nature of the asteroid belt and study up close one of its largest inhabitants, Vesta, with the Dawn space probe. Our visit to Saturn with the Cassini orbiter provides an opportunity to observe its magnificent rings from a variety of breathtaking vistas and to study their structure, dynamical interactions, and potential origin. We close our tour of the solar system with stops at the ice moons Europa and Enceladus, which orbit Jupiter and Saturn, respectively. As revealed by the Galileo and Cassini orbiters, the surfaces of both of these worlds yield strong evidence of internal heating and subsurface oceans of liquid water.

We begin our tour of the Milky Way Galaxy in search of the shadows of Earth-sized planets around other stars with the Kepler Space Telescope. Our next stop is the Swan Nebula, where infrared images obtained with the Spitzer Space Telescope have revealed an evolving pattern of star formation that may have been driven by the passage of its parent dark cloud complex through a galactic spiral arm. The Spitzer image of the nearby Pleiades star cluster provides an infrared perspective on one of the top optical sights in the night sky. This infrared view highlights the spectacular web of fine-scale structure in the cluster's veil of stardust. We next gaze through Hubble for the sharpest view yet of Eta Carinae, one of the most massive stars in the Galaxy. Its dumbbell-shaped debris cloud from a violent eruption in 1843 is merely a prelude to its eventual explosion as a supernova. In contrast, the runaway star Zeta Ophiuchi appears to be fleeing the site of a million-year-old supernova; its infrared Spitzer image reveals an interstellar bow shock that points back to a massive star cluster. We conclude the Milky Way segment of our cosmic tour with a multiwavelength visit to the menagerie of unusual stars, hot gas clouds, and a supermassive black hole in the galactic center region.

Beyond the Milky Way, we focus first on the ultraviolet image of the Andromeda Galaxy provided by the GALEX space telescope and discuss Andromeda's past and future interactions with its galactic neighbors. We then turn to Hubble for a detailed look at some of the most peculiar galaxies in its galaxy album. Hubble also has been vital in imaging the faint host galaxies of distant quasars. We focus on the case of the brightest quasar, 3C 273, in discussing the nature and evolution of these energetic objects. Our next stop is a colliding pair of galaxy clusters known as the Bullet cluster. Hubble and the Chandra X-ray Observatory have teamed up to visualize the invisible dark matter in this colliding cluster and others. In the penultimate lecture, we voyage to the sites of the most powerful explosions in the universe with the Swift space observatory. The brief gamma-ray bursts from these explosions appear to be due to the collapse of very massive stars into black holes at distances typically exceeding 5 billion light-years. We close the course with an exploration of the cosmic microwave background radiation imaged by the WMAP space observatory. As the afterglow of the big bang, this ultimate background frames all of our other topical images in distance and time. ■

Probing the Cosmos from Space

Lecture 1

For the first time in human history, it has become possible to visualize and map a universe that is mostly invisible to the Earth-bound human eye. Observations of the night sky have now expanded beyond the Earth into space with a fleet of spacecraft that have ushered in a new age of cosmic discovery. In this course, you will explore the scientific stories behind some of the most spectacular space images obtained during the past 20 years. In this lecture, you will be introduced to the key motivations and limitations in expanding the frontier of space exploration.

Space Exploration

- When most people think about space exploration, they typically think in terms of human spaceflight and the National Aeronautics and Space Administration (NASA). But most people might not realize that humans haven't been to the Moon or beyond for more than 40 years. Space is expensive, particularly human spaceflight. Humans require air, food, and protection from radiation, among other things.

- In the 1960s, there was a lot of political motivation for the United States to go to the Moon, because Russia was trying to do the same thing. At its funding peak in 1966, NASA was over 4 percent of the United States's budget. Today, it's about 0.5 percent of a larger budget.

- The most obvious target beyond the Moon is Mars. The scientific motivation for Mars is clear and important. The Martian surface is most similar to Earth in the solar system. Evidence of past life would imply that life is common.

- But Mars is much farther away than the Moon. To travel to Mars, it would be about a 6-month journey each way. How do we protect

astronauts from radiation for so long? The realistic cost of a human Mars mission is more than 50 billion dollars.

- We could avoid the various problems with sending a human by sending robotic probes instead. Orbiters and rovers are so advanced that it’s almost the same as being there. This would be more cost effective than sending humans and also much safer.

- The most sophisticated probe ever sent to Mars landed successfully in August 2012. This roving science lab named Curiosity is the size and weight of a small car. It is equipped with a host of cameras and instruments, plus a nuclear power source. Its primary purpose is to determine if Mars once had conditions suitable for life. The total cost of the Curiosity mission is 2.5 billion dollars.

- Its top speed is 1.5 inches per second, or about 0.1 miles per hour. Why is it so slow? When driving a car on Earth, you can see something in your path and brake almost instantaneous. This is not so when driving Curiosity on Mars from Earth.

- When closest, the Earth-Mars distance is 80 million kilometers. The speed of light is 300,000 kilometers per second. The view through the Curiosity “windshield” is always about 4.5 minutes old. We would need more than 9 minutes to stop upon the sight of a big rock or hole in the path. And it would be sad if the first Mars life became the first Mars roadkill.

- This illustrates the key fact that distance equals time in astronomy. Sunlight takes 8 minutes to reach the Earth 150 million kilometers away. Consequently, we see the Sun as it was 8 minutes ago. In terms of light travel time, the Sun’s distance is 8 light-minutes.

- In contrast, Neptune, the most distant planet, is 4 light-hours away. Although vast, this region is within range of our spacecraft. Indeed, NASA has sent probes to all of the planets. The 1989 flyby of Neptune by Voyager 2 took 12 years. The dwarf planet Pluto is next

up, at a distance of 4.5 light-hours. In 2015, New Horizons will fly by Pluto after a 9-year trip.

- Our tour of the Sun, planets, moons, and asteroids in this course will demonstrate how the modern view of the solar system has been transformed by space probes. In the case of Mars alone, we have sent 50 probes to the Red Planet since 1960. Orbiters reveal ancient water flows, but no Martians. Rovers study surface rocks to confirm the evidence of past water. Why has Mars evolved into a cold, dry, nearly airless desert? Did life form on Mars long ago?

- How much farther can we directly probe with our spacecraft? Among all of the space probes ever launched from Earth, the most distant is currently Voyager 1, which was launched in 1977 on a mission to fly by Jupiter and Saturn. It is now 17 light-hours away, leaving the Sun's area of influence into interstellar medium. It is moving 17 times faster than a rifle bullet.

- But the space between the stars is vast. The nearest star is Alpha Centauri, which is 4.3 light-years away. Voyager 1 would need 76,000 years to cover that distance. We will not be going to the stars anytime soon.

The Study of Light

- Our exploration of the universe beyond the solar system is almost entirely based on the study of the light emitted, absorbed, or reflected by distant objects. The light that we see with our eyes is just a tiny piece of a broad spectrum of electromagnetic radiation. This radiation consists of particles called photons.

- The energy of a photon is inversely tied to its wavelength: Higher-energy photons have shorter wavelengths. The electromagnetic spectrum describes photons as function of wavelength. The spectrum runs from gamma rays (< 0.01 nm) to radio (> 1 mm). The optical portion of the spectrum is just 400 nm (violet) to 700 nm (red). Each electromagnetic region gives a different view of the

universe. Hot stars are brightest in the ultraviolet region, while cool stars are brightest in the infrared region.

- This total electromagnetic view makes it to the top of our atmosphere. But much is lost in the final 200 km to the surface. It is transparent only to optical, radio, and select infrared regions. The other electromagnetic regions can only be observed from space. This is the key motivation for gamma-ray, X-ray, ultraviolet, and infrared space telescopes.

- The atmosphere also plays a key role in limiting the sharpness of optical images obtained with ground-based telescopes. Turbulence scatters and blurs incoming starlight. Our eyes see this phenomenon as stars "twinkling." Our eyes have a sky angular resolution of approximately 1 arc minute, which is equivalent to about 1/30 of the full Moon width.

- Telescopes improve on our eyes with bigger lenses and mirrors. A small telescope has resolving power of about 1 arc second. It also collects more photons, which allows us to see fainter objects. The biggest (about 10m) optical scopes could have about 0.01 arc second resolving power, but the atmosphere typically limits "seeing" to about 1 arc second. This is the key motivation for a large optical space telescope.

The Great Observatory Program

- In order to study the universe across the electromagnetic spectrum with high-quality images, NASA launched four large space telescopes between 1990 and 2003 as part of its Great Observatory program. With a wavelength coverage from the ultraviolet to the near-infrared, Hubble was the first of these. And its images have been fantastic.

- The other Great Observatories include Compton (gamma-ray), launched in 1991 and deorbited in 2000; Chandra (X-ray), launched in 1999; and Spitzer (infrared), launched in 2003. There have been over 70 other space telescopes over the past 40 years. Typically,

these have had smaller scopes with a specific purpose.

- Our Milky Way Galaxy is a key focus of the space telescope fleet. The Milky Way is 100,000 light-years across, with 300 billion stars. We live in the thin disk that is 28,000 light-years from the galactic center. As viewed from the surface, the Milky Way disk is a band of light across the sky. Space observations provide multiwavelength view of the Milky Way disk.

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Data from the Kepler Space Telescope indicates that there are billions of exo-earths in the Milky Way Galaxy.

- Our tour of the Milky Way will reveal how the view from space casts new light on the evolution of stars and the interstellar medium in the Galaxy. This view has also enabled a pioneering search for Earth-sized planets around other stars. Such planets are too faint to detect via their reflected light.

- The Kepler Space Telescope searches for exoplanet shadows instead. It monitors 150,000 stars for tiny periodic eclipses in brightness. It is designed to determine if Earth-sized planets are common in the Milky Way. The results to date indicate that there are billions of exo-earths in the Milky Way.

Beyond the Milky Way

- Beyond the Milky Way is a universe of many billions of galaxies. Hubble is exceptional at imaging distant galaxies. Hubble has detected galaxies over 13 billion light-years away. It has witnessed galaxy evolution consistent with the big bang 13.7 billion years ago.

- Our space tour beyond the Milky Way will stretch from the nearby Andromeda Galaxy to the cosmic microwave background that provides the earliest view of the universe. In the case of Andromeda, an ultraviolet image obtained with the Galaxy Evolution Explorer space observatory has revealed a ring structure indicative of a past collision.

- The WMAP view from space of the microwave sky looks back 13.7 billion years ago. We see the universe as it was 400,000 years after the big bang. It was much hotter and denser and was as bright as the Sun's interior everywhere. Tiny density fluctuations then evolved into the galaxies of today. This ultimate background frames the cosmos in distance and time.

- As we utilize NASA's fleet of space probes and observatories to explore the universe in this course, it is important to remember that these instruments are more than just machines. Each one has a team of hundreds to thousands of technicians, engineers, and scientists who have typically devoted at least a decade of their lives to the design, construction, and operation of these sophisticated spacecraft.

- This dedication is reflected in the joy and excitement of the mission control team upon learning of the Curiosity rover's successful landing on Mars. They know better than anyone the potential for thrilling new discoveries as Curiosity explores a new frontier on the Red Planet. While human spaceflight has been confined to Earth orbit over the past 40 years, our robotic space avatars like Curiosity and Hubble have been busy visualizing a universe hidden to our eyes on Earth.

Suggested Reading

Gorn, *NASA*.

Pyne, *Voyager*.

Zimmerman, *The Universe in a Mirror*.

Questions to Consider

1. If you had the resources to send a space probe to just one planet in the solar system, which planet would you choose? Why?

2. Given the success of NASA's fleet of space probes and observatories, what should be the objectives and aspirations of human spaceflight?

The Magnetic Beauty of the Active Sun

Lecture 2

During its first few years in orbit, the Solar Dynamics Observatory has opened our eyes to the rich diversity and complexity of magnetic phenomena on the Sun. Its detailed full-disk extreme-ultraviolet images and movies of loops, flares, and coronal mass ejections are providing new insight on the physics of solar activity, while also illustrating the beauty and power of ionized gas in magnetic motion. Despite its optical constancy in the daytime sky to human eyes, the space view shows that the Sun frequently undergoes magnetic explosions with energies that dwarf anything in our earthly experience. Most of the time, these explosions result in nothing more than a nighttime auroral display on Earth. Other planets haven't been so lucky.

The Sun

- Among all of the objects in the sky, the Sun clearly has the dominant influence on the Earth. Its gravity governs our orbital motion. Its light rules the daytime sky and warms the planet. Life as we know it on Earth would not be possible without the Sun. As it rises and sets in the sky every day, the Sun's optical appearance is a comfortable constant in our lives.

- However, when viewed in detail, the Sun's surface is anything but constant. It exhibits optical patterns of dark spots that vary over time. Such sunspots occur in regions where the Sun's strong magnetic field is poking through its surface. As viewed in the extreme ultraviolet (EUV) from space, the magnetic loops and arcs associated with sunspots are illuminated by the hot gas traveling along them. Since its 2010 launch, the Solar Dynamics Observatory (SDO) has been taking detailed high-time resolution images of the full solar disk, from optical to EUV wavelengths.

- A key goal of the SDO is to better understand how the Sun's complex magnetic field produces the solar flares observed in

sunspot regions. Such flares can explode with an energy over 10 million times that of a 100-megaton nuclear bomb and spew clouds of high-energy particles into space.

Sunspots

- The first step in making sense of sunspots is understanding how the Sun shines. Based on theoretical models and observations of many stars, astronomers have a pretty good idea of how the Sun's energy is produced and how it gets to the surface.

- Given the Sun's mass, 4.6-billion-year age, and mostly hydrogen composition, only the nuclear fusion of hydrogen into helium can account for its current energy output. This process involves smashing hydrogen nuclei (protons) together. It can only occur if the temperature is more than 10 million kelvin and under high pressure.

Sunspots are optical patterns of dark spots that occur on the Sun's surface and vary over time.

- Core fusion produces very energetic gamma-ray photons. Beyond the core, the Sun is still very dense. The photons are scattered many times off of matter particles. This radiative diffusion operates out to 70 percent of the solar radius.

- Photon energy takes about 100,000 years to cover about 400,000 kilometers. As the density thins, the photons cover the last 200,000 kilometers to the solar surface in about 3 months through the process of convection.

- This is similar to a pot of water boiling on a stove. Before heat is applied, all of the water has the same temperature, and there is no boiling. Then, heated bottom blobs are lighter than their surroundings, and they rise. At the top of the pot, the blobs lose heat, become denser, and sink. In the solar case, hot gas parcels rise and radiate photons at the surface. Radiating gas parcels then lose heat and sink.

- Radiated photons have mostly cooled to optical wavelengths. The photosphere is the surface region where the photons escape into space. The temperature of the photosphere is about 5800 kelvin. Detailed optical imaging reveals convection cells in the photosphere.

- Sunspots are dark localized regions on the solar surface that are about 1500 kelvin cooler than their surroundings due to the suppression of convection. They have lifetimes of days to weeks, with sizes about twice that of Earth. Sunspots have magnetic fields 1000 times stronger than Earth. They often appear in pairs where the Sun's field pokes through the surface. It is these magnetic fields that locally suppress convection.

- Sunspots typically last long enough to trace the Sun's rotation. The Sun rotates faster at its equator than the poles. Also, the number of sunspots varies with an 11-year cycle. Sunspot minima start with a few high-latitude spots. As the maxima approach, more appear at lower latitudes.

- How can we make global sense of sunspots? The solar convective zone is a hot gas of charged particles. Such a gas is an excellent conductor of electricity. The gas convection and rotation generates a magnetic field. As the gas moves, the embedded magnetic field is dragged along.

- The Sun's differential rotation twists the field tighter and tighter. As the field lines gets tangled, north-south loops pop above the surface. Models show that the first loops pop at high latitude. As the field

gets even more twisted, they pop toward the equator. After about 11 years, the field is so twisted that it rearranges itself. The sunspots disappear, and a new cycle begins.

- As the loops pop up, they drag hot gas with them. The evolution of these loops can lead to solar flares. Such magnetic activity heats the outer solar atmosphere. Temperature actually rises with height above the photosphere. The tenuous gas in the Sun's corona is over 1 million kelvin. Such hot gas is best observed in extreme ultraviolet/X-ray.

The Solar Dynamics Observatory

- The Solar Dynamics Observatory (SDO) is a multiwavelength space mission designed to study the magnetic activity of the Sun in unprecedented detail, from its photosphere through the corona. Its ability to monitor the Sun at high time resolution 24/7 with sharp full-disk extreme-ultraviolet images is unmatchable from the ground and makes it possible to study the time evolution of sunspots and the explosive phenomena associated with their magnetic activity.

- The spacecraft itself is about the size of a large sport-utility vehicle. In addition to instruments that monitor the Sun's magnetic field and its extreme-ultraviolet spectrum, it has four telescopes designed to image the whole Sun at a resolution better than 1000 kilometers.

- The SDO can take images in 1 optical, 2 ultraviolet, and 7 extreme-ultraviolet wavelength bands. Shorter wavelengths sample higher temperatures at higher solar heights. It can image 8 of these bands every 10 seconds. The SDO sends back 150 megabytes of data per second, 24/7. This is 50 times greater than any other NASA mission.

- The SDO is in an inclined geosychronous orbit at 37,000 kilometers. This puts the SDO in an approximately fixed sky position, like TV satellites. It supports a high data rate. In addition, it is possible to view the Sun 24/7 almost all year. The time-lapse movies that are

producible from so many images are extraordinary in revealing how solar magnetic activity can evolve.

- One of the most spectacular solar flares observed in recent years occurred on June 7, 2011. As viewed over 2 hours with the SDO in the 60,000-kelvin extreme-ultraviolet band, there was a solar flare flash, and then an enormous amount of material was blown into space and fell back on the Sun. The flare itself was of moderate intensity, equivalent to about a million 100-megaton nuclear bombs.

- The 1,000,000-kelvin SDO view shows the bright loop flare and the coronal mass ejection (CME). Its darkness shows that much of it was unusually cool. This was the first SDO CME where much fell back far from the flare. It ejected about 10^9 tons of ionized gas into space at about 1000 kilometers per second, which is equivalent to 10,000 aircraft carriers being hurled at a speed 1000 times faster than a rifle bullet.

- Where does the enormous solar flare energy come from? The details are unclear, but we know that magnetic fields are key. As a loop region expands and stretches, field lines converge. The breaking and reconnecting of these lines releases energy. This energy, the flare, drives the CME.

Geomagnetic Storms

- Why should we care about solar flares and coronal mass ejections (CMEs)? First, the X-rays from intense solar flares can reach Earth in 8 minutes, increase the ionization of the upper atmosphere, and disrupt long-range radio communications. A few days later, if a CME is directed toward Earth, its high-speed bubble of ionized gas will begin to interact with the planet's magnetic field.

- Earth's magnetic field is due to its molten iron outer core. It mostly deflects the solar wind's charged particles. A denser, faster CME pulse can compress the Earth's field. The flood of charged particles can start a geomagnetic storm. Some follow field lines into polar regions. They collide with and ionize air atoms in the

upper atmosphere. Oxygen and nitrogen ions then recombine and emit light of different colors. The resulting auroras occur at 100- to 300-kilometer altitudes.

- Unfortunately, such storms can also create serious problems. For example, the charged particles can damage satellites. They can also induce currents in long electric transmission lines. These can disable transformers and bring down grids.

- A strong 1989 storm cut power to 6 million people in Canada. Much stronger storms have occurred in the past and will occur in the future. The strongest storm in the past 500 years or so occurred in 1859. The aurora could be seen in the Caribbean, and people could read by its light in the northeastern United States. There was widespread disruption of telegraph service. Today, a widespread blackout could take months or years to recover from.

- Can we predict a severe geomagnetic storm well in advance? We know crudely that the fastest, most massive CMEs that produce the

The interaction of the solar wind's electrons and protons with atoms of the upper atmosphere causes auroras.

strongest storms are more likely when the 11-year sunspot cycle reaches its peak of solar activity. The hope is that with the flood of data from the SDO and other solar missions, we can eventually understand solar activity well enough to predict particularly active cycles and perhaps provide more than a few days' warning of a severe geomagnetic storm. However, it will not be easy given the ever-changing complexity of the Sun's magnetic field.

Suggested Reading

Moldwin, *An Introduction to Space Weather*.

Pesnell, "Opening a New Window on the Sun."

Wilkinson, *New Eyes on the Sun*.

Questions to Consider

1. Why doesn't nuclear fusion occur in the solar corona? Why can't it be the direct power source for solar flares?

2. Is the Earth's magnetic field or its atmosphere more important in protecting the surface from the X-ray radiation of an intense solar flare? Why?

Mars—Water and the Search for Life

Lecture 3

With an atmospheric pressure less than 1 percent of Earth's and temperatures typically well below freezing, the surface conditions of Mars cannot currently maintain even puddles of liquid water. However, the existence of riverlike surface features and mineralogical evidence indicate that large-scale flows of liquid water occurred on Mars during the first 1 to 2 billion years of its history. Where did the water go? Was there ever life on Mars? Over the past 40 years, NASA has sent a number of spacecraft to orbit and land on Mars to better address such questions.

Comparing Earth and Mars

- One of the best reasons to study other planets in detail is to gain a better understanding of the physical processes that have shaped the Earth. Let's begin by comparing the similarities and differences of Earth and Mars. The radius of Mars is about half that of Earth. The total Mars surface area is about equal to the land surface area of Earth. The mass of Mars is only about 10 percent that of Earth. A 150-pound person on Earth weighs 55 pounds on Mars.

- Mars is about 1.5 times farther away from the Sun than Earth, and it receives 2.3 times less sunlight than the Earth. Mars exhibits seasons like Earth; its rotation axis has a similar tilt. A Martian day is 24.67 hours, and a Martian year is 1.88 Earth years. Seasons are most noticeable at the polar caps on Mars.

- Hubble offers a view of the north cap from early spring to early summer. As the cap warms, frozen carbon dioxide (dry ice) sublimates into the air. What remains by summer is underlying water ice. The cycling of carbon dioxide between caps generates seasonal winds, which can produce local and global dust storms. As dust settles, it can change the surface appearance.

- Atmospheric surface pressure is less than 1 percent of Earth. The composition is 95 percent carbon dioxide, with traces of nitrogen, argon, and oxygen. The carbon dioxide greenhouse effect only adds about 5°C of warming. The daily temperature range near the equator is about −100°C to 17°C.

- The surface of Mars has a number of interesting features that offer clues to its geological past. The Mars Global Surveyor orbiter shows that impact craters are not distributed evenly. Most impacts are from early (about 4 billion years ago) in Mars's history.

Mars, the fourth planet from the Sun, is similar to Earth in many ways.

- The Tharsis highlands of Mars have a number of extinct volcanoes, including Olympus Mons, the largest volcano in the solar system. It has an Arizona-sized width and a height of 26 kilometers. Why is it so big? There are no earthlike plate tectonics on Mars. Earth's crustal motions spread the impact of mantle plumes, so Earth has a chain of volcanic islands while Mars has one big volcano.

- Higher-resolution surface views of Mars reveal narrow channels. The Mars Global Surveyor orbiter views of a 2.5-kilometer-wide canyon at 12-meter resolution show features that suggest ancient water flows. By age-dating craters, it can be determined that channels were carved about 3 billion years ago.

- Based on these observations, a picture has emerged where Mars might have evolved similar to Earth during its first billion or so years

in terms of its water, atmosphere, and volcanic activity. Indeed, it may have once had a vast Martian sea in its now northern lowlands. A substantial carbon dioxide atmosphere could've provided enough warming through the greenhouse effect to keep the water liquid.

- Mars ended up differently due to its smaller size and mass. This led to more rapid cooling of its molten interior. Volcanic activity slowed, which led to less outgassing of carbon dioxide. It would have also lost its magnetic field. Charged particles from the solar wind would no longer be deflected, and this would slowly strip away the atmosphere.

- Meanwhile, solar ultraviolet light broke up water vapor into hydrogen and oxygen. The light hydrogen atoms escaped the weak Mars gravity. Much of Mars's initial water was lost to space. As the atmosphere thinned, the remaining water froze out at the poles and underground. Some of the underground water may still be liquid.

- The Mars Global Surveyor orbiter has imaged gully systems on some crater walls. Images reveal sharp, flow-like channels at 1.5-meter resolution. A few have revealed changes over the past few years. Perhaps an ice plug on the crater wall breaks and salty water flows briefly. Water quickly vaporizes, leaving a deposit trail behind.

Sojourner

- The search for ground-based evidence of past and present water has been a key science driver for the land rovers sent to Mars over the past 20 years. The first of these missions was Mars Pathfinder, which successfully landed in 1997. It consisted of a base station equipped with weather instrumentation and a camera, plus a small 10-kilogram rover named Sojourner. It wandered out 100 meters amidst a nearby rock field.

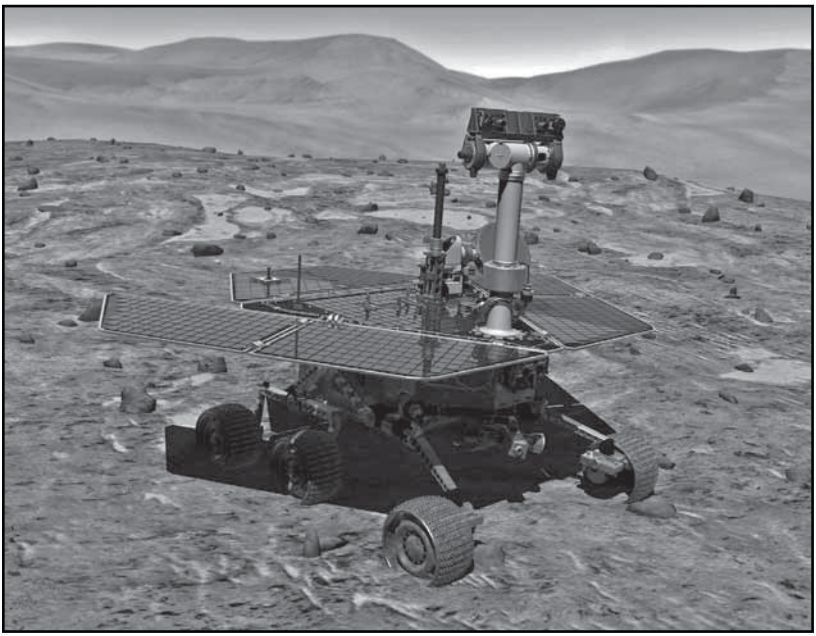
- Equipped with its own cameras and instrumentation, Sojourner measured the composition and rounded shape of the rocks. The findings are consistent with the landing site being an ancient

floodplain. The Pathfinder was a low-cost (about 200 million dollars) proof of concept for bigger rovers.

Spirit and Opportunity

- The Exploration Rovers Spirit and Opportunity successfully arrived on Mars in 2004. Spirit landed in the flat plains of the large Gusev crater, while Opportunity set down half the planet away in a small crater on the plains of Meridiani Planum. These large rovers were equipped for a much longer and deeper exploration of Mars than Sojourner, at a total cost of about 800 million dollars.

- These solar-powered 180-kilogram rovers have a top speed of 2 inches per second. They were designed to overcome holes and rocks, and they have a variety of cameras and instruments that are used to analyze rocks.



Spirit, a rover that was launched from Earth in 2003 and arrived on Mars's surface in 2004, was tasked with studying the chemical and physical composition of the surface of Mars.

- The rovers had a quick, exciting landing after their 7-month trip. In space, the rover and lander are encased in a 2.6-meter-diameter aeroshell. This aeroshell heat shield hits the Mars atmosphere at 5.4 kilometers per second. Within 4 minutes, the atmospheric friction reduces the speed by 90 percent. Two minutes before landing, a parachute opens. Eight seconds before landing, airbags inflate around the rover and lander. It bounces about 25 times over a distance of about 200 to 300 meters. Airbags deflate, the lander petals open, and the rover drives off.

- Some of Opportunity's most photogenic views have come in the vicinity of Victoria crater. This sand-filled crater is about 750 meters across and 70 meters deep, with scalloped edges due to wind erosion.

- Opportunity traveled about 9 kilometers over 32 months from the landing site. Opportunity's first clues to Mars's watery past came at the landing site: rock outcrop on the edge of the small (20-meter) Eagle crater. The layering seen in the rocks likely formed in moving water. These rocks are rich in sulfate-salt minerals, which means that they were soaked with salty water at some point.

- Millimeter-sized "blueberries" are also found in Eagle crater. These are found in other places, too, such as in Endurance crater, which has been imaged by both Opportunity and Spirit. They are similar to those on Earth; they are made of iron-rich hematite. They are formed by the percolation of water through sediments.

- The bottom line is that the rovers have found strong ground-based evidence for a watery past on Mars. They also have provided beautiful other-worldly views. Spirit has imaged the Mars sunset, which has a long twilight due to high-altitude dust.

- There were initial concerns about dust buildup on rover solar panels. But despite the thin air on Mars, cleansing winds keep the power up. The rovers have lasted long beyond their initial 90-day

mission. Spirit lasted about 6 years, while Opportunity has traveled 35 kilometers through 2013.

Curiosity

- The next step in the robotic exploration of Mars is the roving Mars Science Laboratory named Curiosity. Its key science goals include compositional studies of rocks and soil in search of organic carbon compounds and potential biosignatures. Curiosity is 5 times heavier than Opportunity and has a roving lifetime of up to 14 years with its nuclear power source. In August 2012, it landed inside Gale crater, which is 150 kilometers across and over 3.5 billion years old. Mt. Sharp rises 5.5 kilometers from the center of Gale crater.

- This landing site was chosen due to its likely geologic history. The crater filled with sediment when Mars was warm and wet. Martian winds later sculpted out much of the sediment, and Mt. Sharp is the sedimentary mound that was left behind.

- Its exposed clay layers allow a study of Mars's chemical history. Curiosity can look far and already sees these layers. This is truly the most photogenic Mars landing site yet. Curiosity has 8 kilometers to travel to the clay base of Mt. Sharp. It will take 6 to 9 months to reach this region. It already found evidence of an ancient streambed on the crater floor, and the associated ancient rock had key ingredients for life.

- Of course, any life that may have once existed on the surface of Mars is long gone. In addition to a lack of liquid water, the topsoil appears to be devoid of organic molecules.

- Although much of the Mars surface appears similar to Earth desert terrain, such as the Sahara, it could not accommodate even the hardiest of terrestrial microorganisms today. However, we have found microbial life-forms inside the Earth that feed off the hydrogen produced by water interacting with underground rock.

- If life formed on Mars long ago when the surface was warm and wet, perhaps some of it retreated to a warm, wet underground as the surface evolved into a cold, dry desert. As crazy as this idea sounds, the study of life on Earth shows that it has an amazing ability to evolve and adapt to changing environments.

- It is this possibility of past and present life that continues to drive the orbital and surface exploration of Mars. It may eventually lead to humans visiting the Red Planet and extending the search to the deep underground. If evidence of past or present life is eventually found on Mars and is shown to have arisen independently of Earth life, it would strengthen enormously the case for life being common in the universe.

Suggested Reading

Bell, *Postcards from Mars*.

Squyres, *Roving Mars*.

Taylor, *The Scientific Exploration of Mars*.

Questions to Consider

1. Should the human colonization of Mars be encouraged or discouraged if a robotic rover finds evidence of microbial life under the surface? Why?

2. How could humans eventually "terraform" Mars to make it more like Earth?

Vesta and the Asteroid Belt

Lecture 4

Between Mars and the gas giant Jupiter are millions of rocky objects that make up the asteroid belt, which consists of material dating back to the formation of the solar system 4.6 billion years ago. Due to the strong gravitational influence of Jupiter, the asteroids were unable to aggregate into a planet. In 2007, NASA launched the Dawn space probe to explore the two most massive asteroids, Ceres and Vesta. Its images of Vesta have revealed a heavily cratered object with a metal-rich core that is structured much more like a planet than just a big rock. It may well be the last of the large building blocks that merged in the early solar system to form the Earth and the other rocky planets.

The Asteroid Belt

- The asteroid belt can genuinely be considered a fossil of the early solar system. The oldest rocks on Earth are actually refugees from the asteroid belt that have fallen from the sky as meteorites. They collectively set the formation age of the Sun and its orbiting planets, moons, and asteroids at 4.6 billion years.

- The nebular model for the formation of the Sun and its planets begins with the slow gravitational collapse of a dense pocket of gas and stardust in an interstellar cloud. As the pocket contracts, it heats up and rotates faster. Most of the mass forms a protostar in the center. The rest flattens into a disk due to gravity and rotation. This disk of gas and dust coalesces into planets around the star. This formation process takes about 100 million years.

- Let’s focus on the details of planet accretion in the nebular disk. Gaseous hydrogen and helium constitutes 98 percent of the disk material. The rest is mostly hydrogen compounds plus some rock and metals. The inner disk is too warm for water to condense into solid particles.

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The asteroid belt is located between 2.3 and 3.3 astronomical units from the Sun.

- Ice particles only form past the "frost line" at about 2.7 astronomical units. Inside this line, rock/metal particles accrete into bigger and bigger rocks. Collisions of 50 to 100 "moons" lead to the final four inner rocky planets. Outside the frost line, ices allow much bigger ice and rock cores to form. Their gravity attracts hydrogen and helium gas and leads to the gas giants. The solar wind clears out the remaining proto-gas, and the gas giants become scattered, icy leftovers to the far outer solar system.

- So, how do the asteroids in the asteroid belt fit into this picture? Essentially, they are the mostly rocky leftovers from the inner planet formation. Originally, the belt had an Earth mass, or more material. With the frost line in its midst, there was some ice among the rock. Like the inner regions, the belt had likely built up some Moon-sized objects. But young Jupiter's gravity acted to increase their velocities. Faster collisions broke up objects and scattered many out of the belt. Thus, no planet formed, and the belt reduced to a tiny sub-Moon mass.

- Jupiter continues to shape the remaining asteroid belt orbits. Asteroid counts reveal that certain orbit sizes have few asteroids. These Kirkwood gaps, discovered by Daniel Kirkwood in 1866, correspond to orbital periods that are integer fractions of Jupiter's orbital period. These lead to resonances that push asteroids to other orbits.

- Among the larger asteroids, Ceres and Vesta stand out. Ceres is big enough to be classified a dwarf planet, like Pluto. It appears from Earth to be composed of a rock-ice mix. It probably formed just beyond the frost line. The Dawn spacecraft will provide the first close-up view of Ceres in 2015.

- Vesta's diameter is about 15 percent of the Moon's diameter and is 500 times farther away. Not even Hubble reveals much surface detail. Its mass (about 9 percent of the belt) and size indicate its rocky nature. It is the most massive of the rocky belt asteroids.

Vesta and Dawn

- Vesta provides the best opportunity for the Dawn spacecraft to explore the kind of planetesimals that built up the Earth and the other inner planets. Because the asteroids in the belt are spread out over a huge volume, they do not present a serious collision threat for transiting spacecraft. Dawn, about the size of a subcompact car, has a high-gain antenna and three ion thrusters.

- Dawn's mission is the most ambitious mission to use ion propulsion, which uses solar power to accelerate a beam of xenon ions to 40 kilometers per second. After rocket launch, ion propulsion provides slow, steady acceleration—unlike chemical propulsion's quicker, harder thrusts. Ion thrust is also 10 times more efficient. Only 425 kilograms of xenon are needed; Dawn used 275 kilograms over 4 years and 2.8 billion kilometers to Vesta.

- Steady ion thrust led Dawn to an expanding spiral loop trajectory. Dawn also utilized Mars's gravity assist to catch up to Vesta. Then, it utilized ion thrust to slow into survey orbit. Two months later,

it slowed further into high-altitude mapping orbit (HAMO). Two months later, it went into low-altitude mapping orbit (LAMO) 210 kilometers above Vesta. From survey orbit to LAMO, resolution improves by over 10 times.

- Images from Dawn highlight some of Vesta's remarkable features. From these images, it is clear that it has been hit by many other asteroids over time. The "snowman," a set of three big craters, is the most obvious. There is also a huge mountain near the south pole. Global features are also evident in video views of the entire surface. Vesta has twice the surface area of California. The grooves circling most of the equator region are about 10 kilometers wide and about 5 kilometers deep.

- The largest of the snowman craters has a diameter of 60 kilometers. The ages of the large craters are estimated by the number of small craters within them. The largest two snowman craters are both the same young age. Perhaps they were formed by a binary asteroid hit. The smallest snowman crater appears to be even younger.

- Views of the south pole reveal a mountain at the center of a huge crater. This crater, named Rheasilvia, has a diameter of about 500 kilometers. Analysis indicates that it is about a billion years old. It partially covers an older crater spanning about 400 kilometers. The peak at Rheasilvia's center rises about 25 kilometers above the crater floor, making it the second tallest in the solar system next to Olympus Mons on Mars.

- The impacts that formed these two craters had global effects. They probably account for Vesta's oval rather than spherical shape. The equatorial grooves are also likely due to the impact shocks. The Rheasilvia impact itself came close to shattering Vesta. It excavated about 1 percent of Vesta out into the asteroid belt. This Vestoid family of small asteroids has Vesta-like orbits.

- In addition to broad-spectrum images that highlight Vesta's topography, the Dawn camera has several color filters that allow it to explore the mineralogical makeup of its surface.

- Unlike other asteroids, Vesta must have been molten in the past, due to heating from radioactive element decay and impacts. When molten, differentiation would have occurred. Heavy metals (iron) mostly sink to the core, while lighter silicate rocks rise.

- Dawn indicates that Vesta has a high density consistent with differentiation. The best model has an iron core of radius 110 kilometers, surrounded by a rocky mantle and a basalt-rich crust. Thus, Vesta's structure is like a planet and not an asteroid. This suggests that Earth didn't make its own iron core. Maybe it was mostly delivered by large planetesimals.

Near-Earth Asteroids

- Due to gravitational interactions and collisions, many thousands of the millions of asteroids in the belt have been redirected into the inner solar system. The ones that are big enough to have been detected from Earth are almost all are over 50 meters in diameter. Those that have orbits that intersect Earth's orbit are classified as near-Earth asteroids (NEAs). Such redirected asteroids occasionally impact Earth. The most frequent impacts are by objects too small to detect from afar. Most of these are very small and burn up harmlessly in the atmosphere as a meteor.

- But some are big and dense enough to reach the ground as meteorites. About 6 percent of all recovered meteorites are actually pieces of Vesta; they are redirected Vestoids from the Rheasilvia impact. These howardite-eucrite-diogenite meteorites are matched to Vesta by spectral similarities. They are iron-poor and are consistent with the crust on the differentiated Vesta.

- With thousands of larger NEAs intersecting Earth's orbit, the odds are that one of these will eventually make an impact of serious proportions. The good news is that it is extremely unlikely that any

of the largest 9000 NEAs detected and monitored to date will hit us anytime during the next 100 years. However, most of the less-than-50-meter-wide NEAs are undetected so far.

- There was excitement about the discovery of an approximately 40-meter-wide NEA in 2012 labeled DA14. Its orbital track put it within 27,000 kilometers of Earth on February 15, 2013. This is a record-close approach for its size. This only happens about once every 40 years.

- Amazingly, just 16 hours before its flyby, there was a big surprise in Russia. An unrelated, smaller NEA streaked across the sky and exploded. Many automobile dashboard cameras in Chelyabinsk captured the event. At its peak, the explosion was briefly brighter than the Sun.

- The NEA had a 30-kilometer-per-second atmospheric entry 1000 kilometers above China at a shallow angle. About 1 minute later, it exploded 20 kilometers south of Chelyabinsk. About 3 minutes later, a shock wave hit the city. Approximately 100,000 windows were smashed, and more than 1500 injuries needed attention.

- It was the first meteor in recorded human history to cause multiple injuries. It had an explosive energy equivalent to 440 kilotons of TNT, which is 30 times the explosive energy of the atomic bomb at Hiroshima. A lower-altitude explosion closer to the city could've been devastating.

- The size of the meteorite was only about 17 meters across, which is somewhat smaller than the 2012 DA14 asteroid flyby that occurred a few hours later. Such 17-meter-sized objects hit the Earth approximately every 100 years.

- It is amazing to think that the remnants of the planetesimals that built up the Earth 4.6 billion years ago can still impact the planet. As revealed by Dawn, Vesta appears to be the only survivor of the differentiated planetoids that came together to form the inner

planets. Jupiter's gravity prevented Vesta and its shattered brethren in the asteroid belt from forming their own planet. Instead, they continue to be a source of Earth-impacting objects that are no longer massive or frequent enough to shape the planet but certainly sufficient to affect the evolution of the life-forms on its surface.

Suggested Reading

Bell, "Dawn's Early Light"

———, "Protoplanet Close-Up."

Yeomans, *Near-Earth Objects*.

Questions to Consider

1. Would you expect a 1-kilometer-wide, oblong-shaped asteroid to have an iron core? Why or why not?

2. How might the history of life on Earth have been different if Jupiter's gravity had not prevented the accretion of the asteroid belt into a planet?

Saturn—The Rings of Enchantment

Lecture 5

As viewed by the naked eye, Saturn doesn't appear much different from the other points of light in the sky, except that it is much brighter than most and doesn't twinkle as much as the stars. However, as viewed through a small telescope, Saturn is revealed as a planet with bright rings around it. What are these rings? Where did they come from? How old are they? In order to better answer such questions, the orbiting space probe Cassini began a detailed study of Saturn's rings and moons in 2004. It has obtained spectacular images of the rings in shadow and light from a variety of orbital perspectives with respect to the planet and the Sun.

Saturn: The Basics

- Saturn is about 10 times farther away than the Earth is from the Sun. Consequently, the Sun is only 1 percent as bright near Saturn as it is on the Earth. Saturn itself is the second most massive planet in the solar system. With a radius of nearly 10 times Earth's, it dwarfs our planet in size.

- Like Jupiter, it is a gas giant composed mostly of hydrogen. Its gaseous outer layer is over 1000 kilometers deep. It has a liquid (metallic hydrogen) interior surrounding a small rocky core. Overall, Saturn is the least dense planet. In fact, it would float in a big enough bathtub. The key point is that there is no "landing" on Saturn.

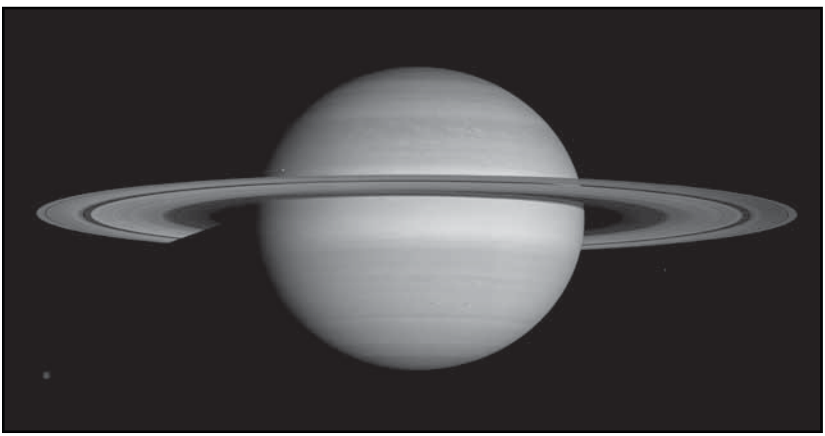
- The size of Saturn is even more pronounced when one considers its rings. The diameter of the outermost bright ring is over 70 percent of the distance between the Earth and the Moon. Over 60 moons, ranging in size from a few kilometers to 5000 kilometers, also orbit the planet. The nine largest moons (all with diameters greater than 200 kilometers) orbit beyond the bright rings. The rings themselves consist of a vast number of dust- to boulder-sized chunks of mostly water ice.

- Why are there rings, and why are no large moons close to Saturn? At the Roche limit, the planet's tidal forces can break up a moon. For a moon orbiting Saturn, the limit is 2.4 times Saturn's radius. Saturn's main rings are all inside its Roche radius.

- Imagine the scenario of an ice moon approaching Saturn. As it nears the Roche limit, it is tidally stretched. At the limit, it is stretched beyond the gravitational breaking point. Broken pieces join Saturn's ring particles.

- The concept behind a ring forming is that different speeds of broken pieces lead to a ring. Collisions and Roche tidal forces prevent a moon from reforming. Is this how Saturn's rings formed—an icy moon came too close? If so, how long ago did this happen? How big was the moon? Alternatively, could rings date back to Saturn's formation?

- Such questions require close ring examination from space. The view from Earth is limited by perspective. As years go by, ring tilt slowly changes. An edge-on view shows that the rings are very thin. We can see this edge-on view every 15 years from Earth. This is due to Saturn's 27-degree ring tilt and 30-year solar orbit.



Saturn, the sixth planet from the Sun, is encircled by rings that consist of mostly water ice.

Studying Saturn Up Close

- Given Saturn's billion-mile distance, there have been only a few efforts to study it up close. The Cassini spacecraft is the fourth to visit Saturn (after Pioneer 11 (1979), Voyager 1 (1980), and Voyager 2 (1981)) and the first to go into orbit around the planet for a long-term mission. It carried a secondary probe named Huygens, which successfully landed on Saturn's moon Titan in 2005.

- With an overall size comparable to that of a school bus, Cassini is the largest interplanetary spacecraft launched to date with a complex array of instruments, ranging from imagers to spectrometers and a 4-meter high-gain antenna.

- There are no obvious solar-power panels. The Sun is only 1 percent as bright at Saturn as it is at Earth. Cassini would need power panels the size of 2 tennis courts. Instead, it is powered by radioisotope thermoelectric generators, which make electricity from the radioactive decay of plutonium.

- Cassini was launched in 1997 with a Titan rocket, and it utilized a looping gravity-assist trajectory to Saturn. It used Venus, Earth, and Jupiter flybys to gain velocity. It covered 2 billion miles in its 6.7-year trip to Saturn.

- It slowed to enter Saturn's orbit with a 95-minute engine burn. It passed within 20,000 kilometers of Saturn's cloud tops. It passed through a ring plane traveling 30 times faster than a rifle bullet. It led with an antenna to shield its instruments. Since its insertion, Cassini has completed over 200 orbits.

- By imaging Saturn's rings in shadow and sunlight from a variety of angles at high resolution, Cassini has revealed their structure in glorious detail. The rings can be seen edge-on with the moon Enceladus in the foreground. Sunlight casts shadows of the three main rings on Saturn: A, B, and C. The C ring is closest to Saturn and casts a faint structured shadow. In images, the darkest shadow corresponds to the densest B ring.

- Another (almost) edge-on view has the moon Titan in the foreground. The Sun is shining on Saturn from above the ring plane. The closest C ring is the top-most shadow. Such edge-on views emphasize the thinness of the rings: Their average thickness is only 20 meters.

- Detailed studies of light interactions with the rings at optical, ultraviolet, and radio wavelengths makes it possible for Cassini to estimate their mass and composition. The Sun is too big and bright for a fine-scale absorption probe. However, Cassini can observe bright stars through the rings—for example, Antares can be seen through the A ring.

- Scanning the star across rings yields the opacity of the structure. These results indicate that the B ring has higher opacity than the A and C rings. This method can also provide indications of clumpiness, which makes mass estimates difficult. The fine structure of ringlets and gaps is also evident.

- Cassini can also probe rings through radio signals to Earth. This can reveal the ring structure down to a resolution of 10 kilometers. It can also yield information on the small end of ring particle sizes. Cassini ultraviolet observations also reveal the most ice-rich ring regions. The trend from outer to inner rings is from cleaner to dirtier ice.

- Thanks to Cassini, we know that clumps of ice particles in the rings are constantly aggregating and breaking up. Collisions and tidal forces keep ice clumps smaller than houses. The total ring mass is about the same as the Saturn ice moon Mimas—although it could be more depending on ring clumpiness. Mimas looks like the Death Star in *Star Wars* due to a 130-kilometer-wide crater on this 400-kilometer-diameter moon. Of Saturn's seven largest moons, Mimas orbits closest to the rings.

Mimas: A Key Player

- The detailed Cassini observations have been especially revealing in terms of the dynamical complexity of Saturn's rings. The images show that they are subdivided into hundreds of thousands of gaps and ringlets, most of them very narrow. The origin of this structure is not yet completely understood. However, key drivers include small moons within the rings and orbital resonances with the larger moons outside the rings. It turns out that Mimas itself is a key player.

- In images from Cassini, Mimas can be seen beyond the A and B rings. The darker Cassini division is between these rings. Particles in the inner Cassini division orbit twice for every orbit of Mimas. This 2-to-1 resonance is like repeatedly pushing someone on a swing. It pushes particles to other orbits and creates the dark gap seen.

- Many ring features are due to the resonances of Mimas and other moons. But the Encke gap in the outer A ring has a different origin. The tiny moon Pan exists within this 325-kilometer-wide gap. Its gravity keeps the gap mostly free of particles. Cassini has resolved the walnut shape of this 30-kilometer object. Pan is just rigid enough to escape tidal breakup. Its gravity wake scallops the inner edge of the Encke gap. A tinier moon is seen in the Keeler gap on the outer A ring's edge. With a size of 7 kilometers, Daphnis also scallops this 42-kilometer gap's edges.

- Cassini has made the rings a lab for many-body gravity physics. But despite the wealth of information from Cassini, the origin and age of Saturn's main rings remain a puzzle. The following evidence points to a young age of less than a few hundred million years.
  - The rings are 90 to 95 percent water ice. Old rings should be "dirtier." The constant rain of small meteors tend to dirty the solar system, but constant ring particle collisions may keep ice "fresh."

  - The rings should spread out and disperse over time. Small-ring moons might prolong ring life, but not for long. Old ring age for Saturn seems unlikely given the dynamic ring activity.

- If the ring age is young, we would need the recent breakup of a Mimas-mass ice moon inside the Roche limit. This is even more challenging if the ring mass is indeed greater than Mimas. Why would this have taken billions of years to happen? Perhaps a massive comet hit the moon, or the comet itself broke up. But such massive collisions most likely occurred billions of years ago.

- Perhaps Saturn's rings formed 4.6 billion years ago along with Saturn, with the migration of a Titan-mass ice moon in a proto-Saturn gas and dust disk. Outer ice layers break up first as the moon moves inside the Roche limit. The rocky core eventually plunges into Saturn, leaving an ice ring behind.

- The mystery behind the age and origin of Saturn's rings only adds to their enchantment. Perhaps Cassini will still reveal the key clues to solve their riddles. Perhaps it will require an even more sophisticated space probe decades from now. Perhaps we'll never be certain. In any case, the beautiful complexity of Saturn's rings will continue to entice the experts and inspire the novices who observe them from near and far.

Suggested Reading

Beatty, "Saturn's Amazing Rings."

Benson, *Planetfall*.

Lovett, Horvath, and Cuzzi, *Saturn*.

Questions to Consider

1. Why doesn't Earth have a ring system of ice particles/rocks like Saturn?

2. Describe the night sky as viewed from Saturn's moon Mimas.

The Ice Moons Europa and Enceladus

Lecture 6

The discoveries on Europa and Enceladus by the Galileo and Cassini space probes have opened our eyes to new possibilities for life in the universe. Coupled with the discovery of life in extreme environments on Earth, we now recognize that even frigid, distant ice moons can have eco-friendly subsurface habitats. As a result, Europa and Enceladus have become high priorities for future space exploration. If we find evidence that life—even microbial life—has arisen in their subsurface oceans, it raises the likelihood that life is common throughout the universe. The odds for life elsewhere would be further increased if it could be determined that earthlike planets are common in our Milky Way Galaxy. Amazingly, we are close to answering this long-standing question.

The Moons of Jupiter and Saturn

- Many of the most fascinating places to visit in the nearby universe are found in orbit around the giant planets of the outer solar system. In addition to its rings, Saturn has more than 60 moons in orbit that are over a kilometer in size. Many of these moons, such as Enceladus, have an icy surface, and some have ice-rich interiors based on their measured densities. Such ice moons are common among the giant outer planets due to the feeble warmth from the distant Sun and the abundance of water in the solar system.

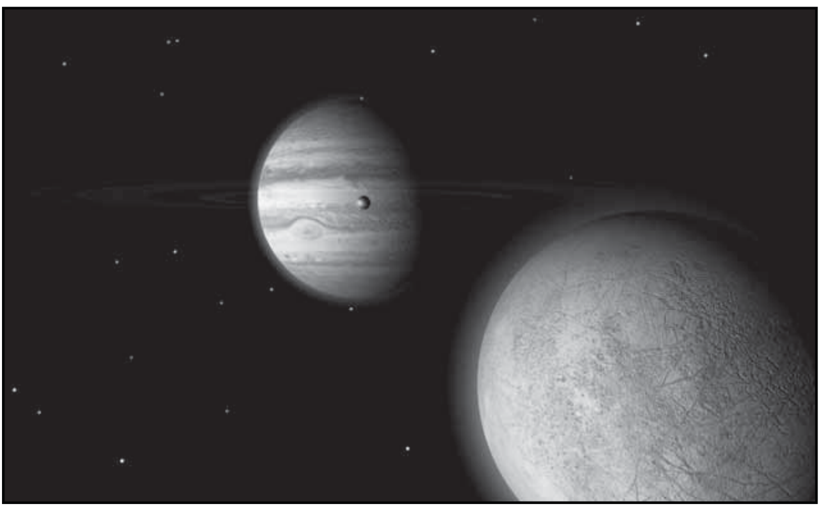
- Before the space probe exploration of Jupiter and Saturn, their moons were expected to be cold and geologically inert, with little internal heating due to their relatively small size. Given that energy and liquid water are key ingredients for life, the ice moons of Jupiter and Saturn appeared to be among the most unlikely places in the solar system to support an extraterrestrial biosphere. However, detailed surface studies of the ice moons Europa and Enceladus with the Galileo and Cassini orbiters have revealed strong evidence of internal heating and subsurface oceans of liquid water.

- The Galileo images of Europa reveal a young icy surface devoid of impact craters, but with a patchwork quilt of ridge features, such as an arctic ice pack. In the case of Enceladus, which has a diameter one-sixth that of Europa, Cassini has found towering surface geysers spewing water and organic molecules into space.

Europa

- Europa is one of Jupiter's four largest moons. These moons were discovered by the Italian astronomer Galileo in 1610, shortly after he began his pioneering sky exploration with a small telescope. As he charted in his notebook, the moons moved nightly with respect to Jupiter. This discovery—that celestial objects could orbit something other than Earth—was key to the eventual acceptance of the Sun, rather than the Earth, as the center of the solar system.

- We now refer to these four moons as the Galilean satellites of Jupiter. Io orbits closest to Jupiter, followed by Europa, Ganymede, and Callisto. Ganymede is the solar system's largest moon. Indeed, it would be classified as a planet if it orbited the Sun. Ganymede's



Europa, one of the four large moons that orbits Jupiter, is a little smaller than Earth's Moon.

diameter is 1.5 times the diameter of Earth's Moon. Europa's diameter is 90 percent that of the Moon.

- Based on its density, Io is made of rock. Europa is mostly rock with some ice. Ganymede and Callisto are a mix of rock and ice. Their surface temperatures are all lower than −150°C. They were all measurable from Earth before space probes, and this fed expectations that they were geologically dead.

- Thus, it was a big surprise when the first close-up view of Io provided by the 1979 Voyager 1 Jupiter flyby mission revealed an active volcano. Its volcanic plume hit an altitude of 100 miles. Io's young surface is dotted with volcanoes and lava flows. Sulfur deposits make it look like a rotting orange.

- What is heating the interior of Io into molten rock? The gravity between Jupiter and Io is 318 times that of Earth and the Moon. Io is also being tugged by Europa and Ganymede. This gives Io a slightly elliptical 1.7-day orbit around Jupiter. This leads to tidal bulges on Io that oscillate in size and location. This constant stretching and squeezing heats Io's interior, which produces 200 times as much heating as radioactive decay.

- What about the ice moon Europa? It is farther from Jupiter, and its orbit is less elliptical than Io. But tidal heating could produce a subsurface ocean. We needed a more detailed study than was possible with Voyager.

- The Galileo space probe was designed to orbit Jupiter and conduct long-term, high-resolution observations of the gas giant and its moons. It was scheduled for shuttle launch in 1985 and to arrive in 1987. It was actually launched in 1989 due to delays and the *Challenger* disaster. Safety concerns led to the use of a slower, solid-fuel booster.

- Galileo utilized a gravity-assist trajectory to Jupiter and Venus and Earth flybys to gain velocity. It covered 2.5 billion miles in

its 6-year trip to Jupiter. Along the way, the main antenna failed to deploy, and data transmission was adapted to a smaller antenna. The data rate dropped about 100 times, but most science goals were still achieved.

- As Galileo passed very close to Europa during several of its Jupiter orbits, it exhibited slight perturbations in its trajectory that provided a better idea of the moon's gravity and internal density structure. It has a dense metallic core and a thick rock mantle. It's topped off by an approximately 100-kilometer layer of ice and/or water. Ice, water, and slush have similar densities. Gravity data allows both subsurface ice and ocean models.

- Global imaging shows that Europa's surface is very young. It is the third shiniest ice moon in the solar system. The few impact craters it has indicate a cycle of resurfacing, which suggests subsurface water/ice breakthroughs.

- Detailed imaging shows Europa's many surface features. Complex networks of cracks and ridges are evident. May form, open, and close due to tidal flexing. The reddish regions are ice-poor and probably salt-rich. This may be due to material brought up from below.

- Some regions show very chaotic terrain, including huge chunks of ice scattered like jigsaw puzzle pieces. Ice-pack patterns resemble the Arctic thawing and refreezing. This is certainly suggestive of warm water rising from below.

- Europa's surface is clearly multi-fractured. This circumstantial evidence indicates a thin ice crust, perhaps no more than 1 to 10 kilometers in thickness. If this is so, Europa's ocean could be 100-kilometers deep. It would have twice the water of all Earth's oceans. However, there are other possibilities. Perhaps this ocean froze up years ago. Perhaps it is an ocean of slushy ice rather than water.

- Galileo found yet one more clue for a liquid ocean. Europa has a weak magnetic field induced by Jupiter. This requires an electric conductor inside Europa. Such a conductor is most likely a salty liquid ocean.

- Even if Europa has a tidally heated subsurface ocean of liquid water, why should this moon be an attractive target to search for life? Its icy surface is brutally cold, with essentially no atmosphere. The intensity of sunlight on Europa is only 4 percent that on Earth, and none of it could make it through even a thin ice crust to the ocean below. However, tidal heating might be sufficient to melt some of the rock in its mantle and drive hydrothermal vents on its ocean floor.

- Such vents and volcanoes are found on the Earth's seafloor. They pump hot water and minerals into the ocean. Such "black smokers" were discovered in 1977. Surprisingly, many vents have thriving ecosystems, despite total darkness and high pressure on the seafloor. Base bacteria feed off the vent's sulfur compounds, and chemosynthesis, not photosynthesis, drives the food chain.

- Could there be such life deep inside Europa's dark ocean? NASA has long-term Europa plans. The ultimate goal is ocean exploration via cryobot. But complexity and cost easily make this decades away. In addition, contamination by Earth bacteria is an issue. Galileo ended its mission in 2003 with a dive into Jupiter, thereby avoiding any chance of contaminating Europa.

Enceladus

- Enceladus is the sixth largest of Saturn's moons and has a size similar to that of England. With a surface that is mostly covered with fresh ice, it is the shiniest object in the solar system. Prior to the arrival of the Cassini probe in 2004, Enceladus was basically regarded as a small, cold ice ball with a curiously young surface.

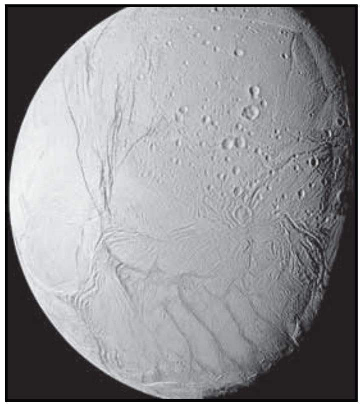
- As Cassini made its initial close passes of Enceladus while orbiting Saturn, the slight alterations in its trajectory indicated that the moon

is denser than originally thought, with a value greater than that of Saturn's other ice moons. Thus, it's likely that there is a rocky core underneath the icy exterior of Enceladus.

- Cassini's images reveal a variety of surface features. There are extensively cratered regions in the north. The younger, smoother south terrain has few craters. Cracks, ridges, and fissures are common everywhere. Most prominent are the "tiger stripes" near the south pole. Cassini infrared images show heat rising from the stripes, which are about 100°C warmer than the −200°C nearby ice.

- The big discovery was ice geysers from the stripes. The geyser plumes reach heights over 100 kilometers. Some of these ice crystals fall back to the surface. Drifts of fresh surface ice suggest that they have more than 1,000,000-year lifetimes.

- Imagine the spectacular surface view. Most of the geyser ice is blasted into space with ejection velocities over half the speed of a rifle bullet. These ice crystals form Saturn's outer ring. Ring maintenance also supports the notion of long geyser lifetimes.



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Enceladus is the brightest moon that orbits Saturn.

- Like Europa, internal tidal heating is likely to play an important role in the geyser activity observed on Enceladus by Cassini. Enceladus orbits close to Saturn with a period of only 33 hours, and its orbit is slightly elliptical. Furthermore, with its rocky core, Enceladus may have a more significant heating contribution from the decay of radioactive elements than would the less-dense ice moons of Saturn.

- Heat leads to subsurface reservoirs of water. These lakes and oceans are highly pressured within the ice. Any vent to the surface means an explosive escape. Cassini images show that Enceladus's stripes flex with its orbit. Such tidal effects open the surface gaps for geysers. Such surface flex suggests a large subsurface ocean.

- Cassini has made passes through geyser plumes and has measured their composition with a mass spectrometer. It has found mostly water, some ammonia and carbon dioxide, and hydrocarbons like propane and acetylene.

- Thus, Enceladus has subsurface organics, water, and heat—in other words, all of life's raw materials. Samples are blasted into space for "easy" analysis. This is an easy flyby compared to the ice drilling that has to be done on Europa. A future mission is to collect samples from Enceladus and return to Earth. The round trip will take less than 15 years.

- Cassini's mission ends in 2017 with a Saturn impact, thereby avoiding any Enceladus contamination.

Suggested Reading

Bennett and Shostak, *Life in the Universe*.

Benson, *Planetfall*.

Greenberg, *Unmasking Europa*.

Questions to Consider

1. Should the contamination of Europa by Earth bacteria be a serious issue in planning its exploration for an underground ocean?

2. If you had the resources to send a fully instrumented orbiter/lander to either Europa or Enceladus in search of life, which would you choose? Why?

The Search for Other Earths

Lecture 7

Thanks to the Kepler mission, we now know that there are many billions of Earth-sized planets in the Milky Way Galaxy, and it is possible that the first Earth-sized, Earth-mass exoplanet in the habitable zone of its host star will be discovered very soon. Within a decade, we will have a large sample of such exoplanets. The search for other Earths will then become a hunt for those habitable worlds that are most likely to support life. It is amazing how much we can learn about exoplanets without actually imaging them. It is also amazing how much we can learn about the Milky Way by imaging it in detail at a variety of wavelengths.

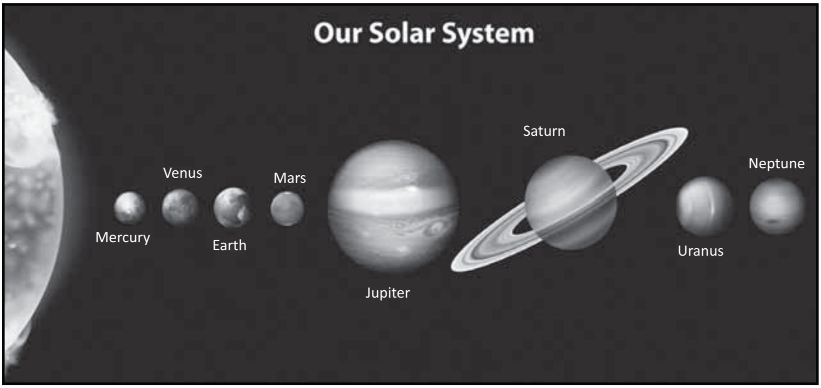
Exoplanets

- The solar system consists of a wide variety of objects orbiting the Sun. The many billions of smaller ones range in size and character, from the rocks in the asteroid belt to the ice moons Europa and Enceladus. The largest ones are the planets, and there are only eight of them.

- The king of the planets is Jupiter, and it has more mass than all of the others combined. Yet this gas giant has no discernable solid surface below its colorful atmospheric features. Among the smaller rocky planets, Mars has similarities to Earth, including its polar ice caps, extinct volcanoes, and thin ice clouds. However, it has no liquid water on its surface and only a very thin atmosphere consisting mostly of carbon dioxide.

- Among all of these worlds, only the Earth has surface oceans of liquid water, an oxygen-rich atmosphere, and abundant life. Is Earth just a rarity in the solar system or a rarity in the entire Galaxy?

- Actually, up until the early 1990s, the only planets known in the entire universe were located in the solar system. Since that time, many hundreds of exoplanets have been found around other stars



using a variety of indirect techniques. Initially, these techniques were only sensitive enough to detect Jupiter-mass exoplanets.

- The Kepler space observatory was launched in 2009 with the primary objective of determining whether or not Earth-sized planets are common in the Galaxy. Kepler detects exoplanets by observing and timing tiny eclipses in the brightnesses of stars as any satellite exoplanets pass in front. During the course of its mission to date, Kepler has detected thousands of exoplanet candidates, of which many are Earth-sized. The holy grail in this effort is the detection of the first Earth-sized, Earth-mass exoplanet orbiting in the habitable zone of its host star.

The 51 Pegasi System

- It has been necessary to develop indirect methods of detecting exoplanets because almost all are too faint to directly image in the glare of their host stars. No ground-based or space-based telescope is currently capable of imaging an Earth-sized or Jupiter-sized planet in an Earth-sized or Jupiter-sized orbit around any solar-type star at optical wavelengths.

- The Cassini eclipse image of Saturn illustrates the problem. In the image, there is a faint point-like Earth just beyond the rings. Imagine trying to see it without Saturn blocking the Sun. Imagine seeing it from the nearest star 30,000 times farther than Saturn. The optical faintness is due to planet size and the source being reflected sunlight.

- Only 30 exoplanets (all big and far from a star) have been imaged (mostly using infrared). The best case is the HR 8799 multiple exoplanet system. Ground-based detection of the near-infrared emission revealed a system of three exoplanets in 2008 and a fourth in 2010. A 2009 study of a 1998 Hubble near-infrared image confirmed the outer three exoplanets.

- All four planets have masses about 5 times that of Jupiter. The innermost planet has an orbital radius 1.5 times that of Saturn. The planets are especially infrared-bright due to the youth (about 30 million years) of the star system.

- The first exoplanet around a solar-type star was found in 1995. It just so happens that this star, 51 Pegasi, is only 2.3 degrees on the sky away from HR 8799 near the Great Square in the constellation Pegasus. Besides being bright, imaging reveals nothing out of the ordinary. It is through spectroscopy that 51 Pegasi yielded a big surprise. The star exhibited tiny velocity "wobbles," which are due to the gravitational tug of an unseen orbiting planet.

- Data from 51 Pegasi showed 55 meter-per-second shifts to and fro over 4.2 days. This is indicative of a 0.5-Jupiter-mass planet 0.05 astronomical units away. This "hot Jupiter" is 8 times closer to 51 Pegasi than Mercury is to the Sun. This was a surprise because massive planets are expected to form much farther out.

- Was the 51 Pegasi system the oddball, or is the solar system the oddball? Most of the initial Doppler exoplanets after 51 Pegasi are also hot Jupiters. But the Doppler method is biased toward such systems. Close, massive planets pull harder on stars and have larger velocity shifts. They also have shorter periods that are faster to detect.

- As sensitivity has improved, many more less-massive planets have been discovered. Over 500 exoplanets have been detected via the Doppler method. Hot Jupiters are definitely not the norm. But it's very difficult for Doppler to detect Earth-mass planets.

The Transit Method

- Given the limitations of the Doppler approach, the transit method is the likely first step in the eventual discovery of an Earth like ours around a solar-type star. Like the Doppler technique, this method is an indirect one, where the exoplanet is not detected through its emission of radiation. It involves searching for the small fraction of stars exhibiting periodic drops in their light output due to transiting exoplanets in edge-on orbits to our line of sight.

- In June of 2012, Venus provided a close-up example. It transited across the Sun's disk over the course of a few hours. We won't see it aligned again on Earth until 2117.

- The stars are too far away to see as anything but points. Exoplanets won't be visible as small, dark disks, but stars will show periodic brightness drops. In the case of a solar-sized host star, a Jupiter-sized exoplanet transit dims light 1 percent, and an Earth-sized transit dims light 0.01 percent.

- More than 100 transiting exoplanets have been discovered from ground observation. These are mostly all large, close-in exoplanets. We need to get above the atmosphere to detect Earth-sized exoplanet transits. Space also provides continuity for complete orbit coverage.

- The Kepler space observatory was launched by NASA in 2009 with the primary goal of determining if Earth-sized exoplanets are common. It is essentially a really big camera designed to take a picture of the same 150,000 stars every 30 minutes in a single part of the sky. By monitoring so many stars simultaneously, Kepler insures that many edge-on systems will be sampled. Specifically, if Earth-sized exoplanets are common, Kepler is expected to detect hundreds over the course of its multiyear mission.

- Kepler is the size of a car, with a 1.4-meter mirror. The heart of the instrument is its 95-megapixel detector array, which consists of 42 charge-coupled devices each with 2200 × 1024 pixels. Kepler's field of view covers 115 square degrees in the constellation Cygnus. This is equivalent to about 0.3 percent of the entire sky. It is located just above the Milky Way to maximize the number of stars without overcrowding. Each pixel covers 16 square arc seconds on the sky.

- Kepler was launched into an Earth-trailing orbit around the Sun. With no Earth occultations, it falls behind at a rate of about 7 days per year. The spacecraft rolls 4 times per year to keep its solar arrays pointed at the Sun. It's always in a position to continue observing its field of view in Cygnus.

- Because the transit method is most sensitive to large planets with short orbital periods, it was no surprise that the first new exoplanets discovered by Kepler were appreciably larger than Earth with periods of a few days.

- Identifying an exoplanet candidate requires three transits. The first transit raises a flag, and the second similar transit sets the period. If the third similar transit occurs at this period, the candidate is confirmed. Thus, a 5-day period takes a minimum total of 10 days to confirm. A 1-year orbital period (like Earth's) would take 2 years to confirm. Kepler has also detected exoplanet systems around some stars.

- As of Jan 2013, Kepler has detected 2740 exoplanet candidates based on its first 22 months of data. These planets are plotted here as a function of their size and orbital period. With each yearly data release, there is an increasing number of smaller-sized planets detected. This trend reflects the greater sensitivity provided by a longer time base to sum more individual transit profiles and convincingly detect the shallow light drops of smaller planets.

- The statistics show that these small planets are common. In fact, 20 percent of solar-type stars have a super-Earth with a period of less

than 150 days, while 17 percent of solar-type stars have an Earth-sized planet with a period of less than 85 days.

- Over time, Kepler will detect more Earths with longer periods. The bottom line is that the Milky Way has billions of Earth-sized planets. But are these Earth-sized planets actually like Earth? The habitable zone is the orbital region where surface liquid water can exist. Factors include stellar luminosity, planet atmosphere, etc. In our present solar system, only Earth is in the habitable zone.

- Earths detected by Kepler so far are closer than Mercury to the host star. None of them are in the habitable zone. A case in point is the Kepler-20 planetary system, which consists of two Earth-sized planets: Kepler-20e and Kepler-20f. They are sandwiched between three larger planets. All five are closer than Mercury to their solar-type star. The surface temperatures of Kepler-20e and Kepler-20f are about 760°C and 430°C, respectively.

- Kepler-22b is the first transiting planet found in the habitable zone. Kepler-22b orbits 0.85 astronomical units from its solar-type star. If its atmosphere is like Earth's, then it has a surface temperature of about 20°C. If its mass and composition are poorly constrained, it could be an ocean world.

- The case of Kepler-22b highlights a key limitation of the transit method: It typically does not provide a tight constraint on an exoplanet's mass, like the Doppler method. If both the size and mass of an exoplanet can be measured, its overall composition can be estimated based on the derived density.

- For example, a water world would be bigger than a similar-mass rocky planet. Depending on the water world temperature, it might be a steam world, ocean world, or ice world. Our best bets for life would be warm rocks or ocean worlds of approximately Earth's size.

- There is a current list of 25 potentially habitable exoplanets. However, none are Earth-sized; all are super-Earths. Most—18 of

the 25—are Kepler exoplanet candidates with size only. Over 70 percent of such candidates were eventually confirmed.

- The Kepler map of Earth-sized planets as of January 2013 shows that all are too close to their host stars to be habitable. But soon, more Earth-sized planets will be found farther out. Some of those will be in the habitable zone with known masses. The map will become a target list of warm rocks and ocean worlds.

- A future telescope will be able to take infrared spectra of these exoplanets. Such spectra will allow studies of their atmospheres. We can then compare them to those of Earth, Venus, and Mars. This could reveal water, ozone, methane, carbon dioxide, etc. The relative mix of these gases will help us find a true Earth. Furthermore, they could provide strong evidence of life.

Suggested Reading

Bennett and Shostak, *Life in the Universe*.

Kasting, *How to Find a Habitable Planet*.

Lemonick, *Mirror Earth*.

Questions to Consider

1. Why might it be advantageous for Kepler to search for the transits of Earth-sized exoplanets around stars that are smaller in size than the Sun?

2. What other factors besides the distance from the host star should be involved in evaluating the surface temperature of an Earth-sized exoplanet? Could the shape of the exoplanet orbit (circular or elliptical) influence its habitability?

The Swan Nebula

Lecture 8

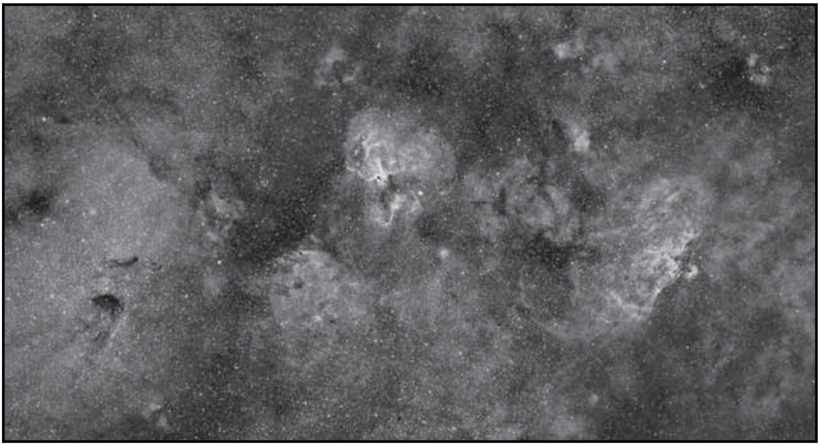
As viewed in detail through an optical telescope, many of the dark clouds in the Milky Way are associated with nebulas of glowing gas. With a diameter of about 20 light-years at its distance of 7000 light-years, the Swan Nebula is one of the brightest gaseous nebulas in the sky. It is part of a star-forming dark cloud complex that stretches over 200 light-years in length and has a total mass over 200,000 times that of the Sun. The Spitzer Space Telescope's infrared view of the entire Swan Nebula region reveals a wide variety of detail inside its dusty gas clouds that is hidden at optical wavelengths.

One of the Brightest Nebulas

- Many of us can recall the first time that we really saw the night sky from a truly dark location. The most striking aspect of such a view is the sheer number of stars observable with the naked eye. Such a view also makes it clear that the stars are not scattered randomly across the sky. Specifically, it is hard to miss a diffuse band of light with embedded dark patches stretching from horizon to horizon. This band is called the Milky Way. It is home to the 300 billion stars and the dark clouds of dust and gas that comprise the disk of our Galaxy.

- The constellation of stars known as Sagittarius lies amidst the Milky Way in the direction of the galactic center. Its brightest stars are easily recognizable to the naked eye in the form of a teapot. The Swan Nebula is about 9 degrees or 18 full-moon widths north of the teapot top.

- Because the Sun is located inside the dusty disk of the Milky Way, our optical view of its structure is rather restricted. However, various techniques, including infrared and radio observations, have allowed us to map the Galaxy.



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Images of the Swan Nebula taken by the Spitzer Space Telescope show details of its gas clouds that are usually hidden at optical wavelengths.

- It has a thin (about 1000 light-years) stellar disk that is about 100,000 light-years across. The Sun is located 28,000 light-years from the galactic center. A bulge of stars surrounds the center out to 3000 light-years. A sparsely populated stellar halo surrounds the disk. Most notable are about 200 globular cluster “star islands.”

- Through the halo, other galaxies can be observed. We have edge-on examples of the Milky Way from afar, like NGC 891, which looks like a thin, dusty stellar disk with a central bulge. Viewed face-on, such galaxies exhibit a spiral structure.

- M74 is a classic example of a spiral galaxy. Its spiral arms are traced in blue by hot, young, massive stars. Its reddish arm regions are due to nebulas near hot stars. Dusty, dark cloud regions are also evident in the arms. Clearly, spiral arms are associated with star formation.

- Radio observations of hydrogen gas support the Milky Way’s spiral disk structure. Its nearby spiral arms are traced by hot, young stars; nebulas; etc.

- The structure of spiral galaxies like the Milky Way and the association of star formation with the spiral arms are best understood in terms of density waves. Rotating-disk galaxies develop in areas of greater mass density. These density waves rotate slower than the stars and gas outside the waves. Both stars and gas slow down as they encounter waves.

- The compressed gas and dust clouds begin star formation. The young, luminous, hot, blue OB stars are the most evident. Their ultraviolet radiation heats the nearby gaseous nebulas. As stars and clouds move past the arm, star formation ebbs. Luminous, blue OB stars die first (in a few million years). Thus, the arms stand out in blue (along with red nebulas).

- As viewed at optical wavelengths, the dark clouds associated with the Swan Nebula in the Sagittarius arm are evident as regions of lower stellar density. The number of stars seen in these regions is consistent with the expected stellar foreground for a Sagittarius dark cloud complex 7000 light-years away.

- The power of infrared observations to peer inside and beyond a dust cloud is best shown with a small, nearby, dark cloud that has no foreground stars. For example, Barnard 68 is 500 light-years away and 0.5 light-years across. As wavelength increases into infrared, more stars are visible through the cloud.

- The cloud's dust absorbs and scatters optical wavelengths more efficiently than infrared. The grains are mostly submicron-sized carbon, oxygen, and silicon particles (smog). Longer-wavelength infrared is less scattered by such small particles.

- Infrared is also more sensitive than optical to cool objects. Stars, planets, and dust can be approximated as blackbody radiators. The spectra of such objects peak as a function of temperature. With a surface temperature of 5800 kelvin, the Sun peaks in the optical. In contrast, a dust-enshrouded protostar could be about 500 kelvin. Such an object would only be detectable in the infrared.

The Spitzer Space Telescope

- The Spitzer Space Telescope was designed to explore the universe in the large part of the infrared spectrum that is unobservable from the Earth's surface. With instruments optimized for wavelengths from the near- to far-infrared, Spitzer is sensitive to both stars and dust at a variety of temperatures within dark clouds. The Infrared Array Camera (IRAC) is a 256-by-256-pixel-array four-band near/mid-infrared camera. The Infrared Spectrograph is a mid-infrared spectrograph suited for composition studies. The Multiband Imaging Photometer for Spitzer (MIPS) is a smaller-array three-band far-infrared camera.

- These instruments are fed by a 0.85-meter-diameter mirror. They are made of strong, lightweight beryllium and are designed to operate at low temperatures. Low temperatures are important for infrared observations. They minimize the contaminating heat of the telescope or instruments. A cryostat filled with 360 liters of liquid helium coolant is designed to cool the telescope and instruments down to about 5 kelvin.

- The Spitzer Space Telescope launched into Earth-trailing heliocentric orbit in 2003. In this orbit, Spitzer drifts away from Earth about 0.1 astronomical units per year. It thereby avoids the 250-kelvin Earth-heat in the near-Earth orbit. This helped the coolant last for almost 6 years, until 2009. Since then, it has been observed only with the IRAC 3.6- and 4.5-micron bands.

- The Spitzer observations of the Swan Nebula region were obtained as part of two large-scale IRAC and MIPS surveys of the galactic plane that were completed before the coolant ran out. In a composite of IRAC 3.6- and 8.0-micron and MIPS 24.0-micron images, the blue, green, and red colors are assigned to 3.6-, 8.0-, and 24.0-micron brightnesses.

- The stars typically appear blue due to their relatively high temperatures. The widespread green glow is due to nebular emission at 8.0 microns. This arises from the ultraviolet excitation

of large molecules. Diffuse red patches are due to warm dust. The brightest infrared region corresponds to the optical Swan Nebula.

- By combining the infrared color information with the morphology of the gas and dust they illuminate, it is possible to trace the evolution of star formation in the Swan Nebula region, which can be broken down into three components associated with the passage of this cloud complex through the Sagittarius spiral arm: star-form dark cloud to star-form nebula to remnant bubble.

- The black patches in the first region are due to dense, cold dust clouds. Thus, they appear dark even in infrared images. This "dragon" of infrared dark clouds stretches about 150 light-years. A detailed study shows that 488 young stars are associated with the dragon. Infrared colors indicate that some have dust shells and some have disks. These represent various stages in the star-formation process.

- The process begins with triggered pockets of gravitational collapse in a dense cloud. As its gas-and-dust core contracts, it heats up and becomes infrared-visible. As the protostar contracts, it also rotates faster. It forms a dusty disk around the protostar with a warmer infrared signature. Over millions of years, the disk may become a planetary system.

- The infrared colors also provide stellar mass estimates. Interestingly, no massive O stars are among the dragon's newborn. Perhaps the formation of O stars occurs after the initial starburst. They are illuminated and shaped by radiation and winds of many massive stars. The dragon may become a Swan Nebula if and when the O stars turn on.

- A more detailed Spitzer close-up on the Swan Nebula uses a mix of IRAC 3.6- (blue), 4.5- (green), 5.8- (orange), and 8.0-micron (red) images. An encircled cluster of 35 massive stars drive the action. It has 9 massive O stars, each with 100,000 to 1,000,000 times solar luminosity. O-star winds blow ionized gas at more than 1000 times

rifle bullet speed. Upstream of the O cluster are "bow shocks," where O winds hit weaker winds of less-massive stars.

- O winds and radiation have opened an optical window into Swan. They also show the sculpting of the interior nebular gas-and-dust wall. An optical Hubble image reveals the wall in greater detail. In a close-up on a 3-light-year section at a resolution of 500 astronomical units, O-star evaporation sculpts the cavity down to dense gas and dust. When O stars turn off in about a million years, the cavity will remain.

- Spitzer reveals such a cavity left of the Swan Nebula. This bubble appears to be 2 to 5 million years old. As it passed the Sagittarius arm, it may have looked like the Swan. Its O stars are now gone; its nebula is much fainter. The cavity's interior is illuminated by the remaining stars. An epoch of massive-star formation in this location is finished. But the bubble's expansion is triggering new modest-star formation. Spiral arms may be a global trigger, but star formation can propagate. Spitzer has revealed many bubbles hidden from optical view inside the dusty clouds of the Milky Way.

Suggested Reading

Hartquist, Dyson, and Ruffle, *Blowing Bubbles in the Cosmos*.

Rowan-Robinson, *Night Vision*.

Waller, *The Milky Way*.

Questions to Consider

1. Why hasn't the process of star formation already converted all of the interstellar gas and dust in the Milky Way into stars?

2. The radiation emitted (not reflected) by living humans and dust-enshrouded protostars both peak in what part of the electromagnetic spectrum?

The Seven Sisters and Their Stardust Veil

Lecture 9

The Spitzer image of the Pleiades provides a different perspective on one of the top sights in the night sky. At optical wavelengths, the bright blue stars of the cluster stand out amidst wisps of nebulosity. In the color-enhanced infrared, this veil of stardust takes front stage with its spectacular web of fine-scale structure. This chance encounter with the bright blue Pleiades stars has illuminated a cloud of stardust into a shining infrared veil. It turns out that the most massive stars can have an even more dramatic effect on their surroundings.

The Pleiades

- As we scan the night sky, our eyes are naturally drawn to the brightest stars in search of recognizable patterns. Since ancient times, various cultures have mapped and navigated the sky in terms of such patterns. Building up their traditions, modern astronomers have established a global sky map covered by 88 of these stellar constellations.

- Unlike a constellation, a star cluster is a group of stars that are physically associated with one another. The brightest and most famous star cluster is the Pleiades. It is easily recognizable to the naked eye as a tight group of at least 6 stars. It is located about 20 full-moon widths away from the bright star Aldebaran in the constellation Taurus. The brightest stars in the Pleiades are named after the Seven Sisters in Greek mythology and their parents. The cluster has been known since antiquity by many other names, including Subaru in Japan.

- As viewed in detail with a ground-based optical telescope, many more of the thousand stars comprising the Pleiades cluster come into view. Even more striking is the bluish nebulosity associated with the brightest stars. When observed at infrared wavelengths with the Spitzer Space Telescope, this nebulosity appears to be

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The Pleiades, an open cluster of young stars, contains more than 1000 stars.

pervasive in the Pleiades region. Indeed, it appears that the Seven Sisters cluster is covered by a wispy veil of stardust heated by the star cluster.

- Are we observing a situation where the Pleiades stars are emerging from their remnant birth cloud of interstellar gas and dust, like the Swan Nebula? Or is this beautiful image the result of a chance encounter between the star cluster and an interstellar cloud along its path?

The Classification of Stars

- Given that the Pleiades is bright enough to be easily seen with the naked eye, one might guess that the cluster is relatively nearby as compared to the other stars in the sky. However, the apparent brightness of a star is a function of the star's distance and its intrinsic luminosity. How do we sort out these factors?

- Fortunately, there is a very straightforward way to determine the distances to nearby stars. It involves stellar parallax: the measurement of a star's position change from two points of view.

- Imagine that we observe a star in January and July, when the Earth is on opposite sides of the Sun. A nearby star's position shifts with respect to distant stars. It can be shown that d(parsecs) = $1/p$(arcsec). An arc second is just a tiny angle. The full moon has an angular extent of 1800 arc seconds. A parsec is equivalent to 3.26 light-years.

- All of the stars in the sky have $p < 1$ arc seconds. As d increases, p decreases beyond measure. Parallax only works for nearby stars (< 200 parsecs). The Pleiades parallax distance is about 130 parsecs, or about 420 light-years. This makes it one of the nearest star clusters.

- Knowing the distances to the Pleiades and other nearby stars makes it possible to determine their luminosities and relate them to other stellar characteristics. A star's brightness decreases with d^2. For example, doubling d decreases the brightness by 4 times. If you can measure the brightness and determine the distance of star, you can learn the star's luminosity.

- You can also measure brightness as a function of wavelength. A prism can be used to break up starlight into colors, like a rainbow. Such stellar spectra reveal absorption lines due to atoms and molecules in the star's atmosphere.

- You can classify stars based on their optical spectrum appearance. The spectral types OBAFGKM are linked to the star's surface temperature. Hot blue O-type stars have highly ionized lines, and cool red M-type stars have molecular lines.

- Patterns emerge when luminosity and type are compared. Such plots are called Hertzsprung–Russell (H–R) diagrams. Most stars are found in the band called the main sequence, which is where stars

spend most of their energy-producing lives. Main-sequence stars are powered by the core nuclear fusion of hydrogen into helium.

- Stars above and below the main sequence constitute later-life stages. Main-sequence stars exhibit a spectrum of properties as a function of type. These properties are determined through observations and stellar models. Type-O main-sequence stars have the most mass, the most luminosity, and the shortest lives. Type-M main-sequence stars have the least mass, the least luminosity, and the longest lives. The Sun is a middle-aged G main-sequence star. It has lived 4.6 of its expected 10-billion-year main-sequence life.

- In essence, the H–R diagram can be used to chart the life histories of stars. Because the stars in a star cluster are typically all born at about the same time, the main-sequence population in their H–R diagrams can reveal the cluster age.

- The Pleiades H–R is missing O and some B main-sequence stars. These stars have used up their core hydrogen and have evolved off the main sequence. The longest lived of these "missing" main-sequence stars gives the cluster its age. The Pleiades main-sequence "turnoff" age is about 100 million years.

- The Pleiades is one of about 1000 "open" star clusters found in the Milky Way. These open star clusters are loosely bound by gravity as they form in their natal, or birth, cloud. The cluster gradually disperses as it orbits in the Milky Way.

- The youngest star clusters are associated with natal gas and dust. The Rosette Nebula cluster is only a few million years old. Its O stars excite the glowing nebular gas. The double cluster h and c (chi) Persei is about 10 million years old. Its many stars are a spectacular sight through a small telescope. It's about 2 full-moon widths across and 7000 light-years distant.

- The nearest star cluster is the Hyades; it is 150 light-years away. Its approximately 300 stars are about 18 full-moon widths from

the Pleiades. Its age is about 650 million years with no O or B main-sequence stars. One of the oldest open clusters at 7 billion years is NGC 188. Its 150 stars are clustered at a distance of 5000 light-years. It is missing O, B, A, and some F main-sequence stars. Cluster differences are easily seen in a composite H–R diagram. As the cluster ages, main-sequence turnoff moves steadily down the main sequence.

- With an H–R lifetime of 100 million years, the Pleiades cluster is well past the age when star clusters typically escape from and disperse the cloud of gas and dust from which they formed. However, the blue nebulosity in optical images of the Pleiades does not appear to be a distant background or foreground.

- It tends to be brightest near the brighter stars. It is a textbook example of a reflection nebula. It is produced by a cloud of dust grains near a star. It redirects some incident starlight toward the observer. A brighter star with a closer dust cloud leads to a brighter nebula.

- The Pleiades stars are within a light-year or so of a dust cloud. Its blue color comes from the fact that its dust grains scatter blue light more than red light. The shorter blue wavelengths are closer in size to the tiny grains that are doing the scattering. There is a similar idea behind the Earth's blue sky: Air molecules scatter blue light across the sky. This is also why a rising or setting Sun often appears red.

- About 500 reflection nebulas have been identified in the Milky Way. The photogenic Witch Head Nebula is another famous example. It is about 900 light-years distant and is much fainter than the Pleiades Nebula. It is illuminated by the blue supergiant star Rigel, which is about 40 light-years away from the Witch Head Nebula.

Merope

- The Pleiades reflection nebula tells us that there is dust in close proximity to the cluster. This optical view of the blue starlight scattered by the dust is most sensitive to the grains closest to the brightest blue stars. In contrast, the infrared view from the Spitzer

Space Telescope provides a deep image of the radiation emitted by the warm dust throughout the Pleiades region.

- The Spitzer image covers 1 square degree, or about 4 full moons, on the sky. It is a composite of images taken with Spitzer's mid-infrared IRAC and far-infrared MIPS cameras. It includes images in the 4.5-, 8.0-, and 24.0-micron bands. Blue, green, and red colors are assigned to these wavelengths, respectively.

- Stars typically appear blue due to their relatively higher temperatures. The diffuse green light we see throughout the Pleiades region arises from large molecules called polycyclic aromatic hydrocarbons (PAHs). Ultraviolet starlight excites PAHs to glow at wavelengths near 8.0 microns. The red regions are due to the warm dust emission. Various yellows and oranges are dust-PAH mixtures.

- A wispy, filamentary structure seems commonplace throughout the Pleiades nebulosity. The origin of this structure is not at all clear. The Pleiades star Merope is amidst the brightest reds and yellows in the Spitzer image that correspond to the densest dust and gas in the nebulosity.

- A close-up of the 1.5-light-year region around Merope reveals the filaments in greater detail. We can see features down to resolutions of about 400 astronomical units. This is suggestive of a nebular interaction with the star.

- Optical images show a bright knot (IC 349) close to Merope. It is located just 3500 astronomical units south of the star. Hubble has imaged IC 349 at a resolution of about 10 astronomical units. At the top if the image are scattered starlight rays due to telescope optics. The tiny reflection nebula shows amazing small-scale structure. Long, thin tendrils extend past its wispy main body. Smaller grains in the body are slowed by radiation pressure. The picture indicates that the cloud is moving with respect to the star.

- The apparent motion of IC 349 relative to Merope is consistent with the velocities measured spectroscopically through the Doppler effect for the other Pleiades stars and the gas associated with the reflection nebulosity. This tells us that the cluster is moving at a speed of about 11 kilometers per second relative to the nebula. Given the cluster motion and its age, it is not a natal cloud. Pleiades is actually just passing through a diffuse cloud region.

- A deep, wide-field view shows other faint clouds. As it moves, it may brighten some of these in less than a million years. Over time, hundreds of millions of years, its B stars will evolve off the main sequence. The reflection nebula potential will decrease accordingly.

- Also, over such times, it will travel far through the Milky Way. It will complete a galactic "orbit" every 200 million years. It will interact with denser clouds and other stars. Over time, gravity will peel off star after star. Within a few orbits, the Pleiades is likely to disperse.

- The Sun was likely born a star cluster member about 4.6 billion years ago. It is now orbiting solo at 240 kilometers per second around the galactic center. Its brothers and sisters evolved or dispersed long ago.

Suggested Reading

Pasachoff and Filippenko, *Cosmos*.

Rowan-Robinson, *Night Vision*.

Waller, *The Milky Way*.

Questions to Consider

1. Describe the differences in the optical and infrared views of the Pleiades and its surroundings if the cluster were 1 billion years older.

2. Besides measuring its stellar parallaxes, how else could we determine that the Pleiades is relatively nearby?

Future Supernova, Eta Carinae

Lecture 10

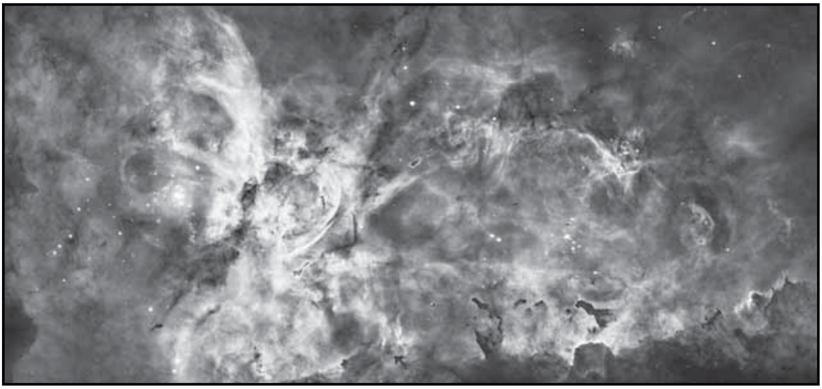
The Carina Nebula is a vast molecular cloud region where the births and deaths of many massive stars over the past few million years have sculpted and illuminated a complex nebular structure. With a luminosity several million times that of the Sun, Eta Carinae is the nearest example of a rare type of star whose brightness can vary dramatically over time due to large mass-loss episodes. As viewed by Hubble, Eta Carinae is surrounded by an expanding dumbbell-shaped debris cloud that was produced by a violent eruption in 1843. Such outbursts are merely a prelude to its eventual explosion as a supernova sometime during the next several hundred thousand years.

The Births and Deaths of Stars

- The trajectory of a star's life and death is largely determined by its initial mass. Observations and theoretical models show that stars born with more than 8 solar masses evolve quite differently off the main sequence than those of lower mass. Over 99 percent of the stars in the Milky Way, including the Sun, belong to this latter group. After nuclear fusion has exhausted the core hydrogen in these stars, they evolve into red giants.

- The Sun will undergo this transformation in about 5 billion years. The core begins to contract slowly because there's not enough nuclear energy being produced to hold off gravity. As the core contracts, it heats up. Then, the shell of hydrogen around this now-helium core gets hot enough to ignite hydrogen into helium fusion. Eventually, millions of years later, this helium core, which continues to contract slowly, will become hot enough to burn helium into carbon and produce energy.

- With these energy sources, the solar surface will expand out to almost Earth's orbit. During this expansion, the Sun's surface will



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Eta Carinae, one of the most massive evolved stars in the Milky Way, might be our next supernova.

redden as it cools from 6000 to 3000 kelvin. The Sun will be a red giant for about 1 billion years.

- The Sun will spend its final few million years as a red giant powered by helium fusion into carbon in a shell around the core. This leads to thermal pulses that will blow off the Sun's outer layers. The Sun will lose about 40 percent of its mass as a red giant. Its exposed core will cause this expanding gas shell to light up as a nebula.

- Such objects are called planetary nebulas—for example, the Ring Nebula. There are many of these in the Milky Way, despite their short life of about 50,000 years. This is consistent with 99 percent of all the stars in the Milky Way evolving this way.

- What's left behind after the planetary nebula stage is a faint, dense, carbon-rich white dwarf star. It's about the size of Earth with the mass of about half that of the Sun. In fact, a teaspoonful would weigh several tons. It slowly cools like a dying fireplace coal.

- In contrast, stars of 8 solar masses or more evolve much more dramatically off the main sequence and leave behind much denser, compact objects. In these cases, core hydrogen fusion is followed

by core helium fusion, followed by a sequence of carbon, neon, oxygen, silicon core fusion. When such a star becomes a supergiant, the surface expands beyond the size of Mars's orbit. Such supergiant luminosities can reach 1,000,000 times that of the Sun. Supergiant lifetimes are only about a million years.

- If we could take a snapshot of the deep interior of such a star during its last hour, it would look just like an onion. In its deep insides, it would have mostly an iron core encircled by silicon, oxygen, neon, carbon, helium, and hydrogen fusion shells.

- Iron does not produce energy through fusion. With no core energy source, gravity is unopposed. In less than 1 second, the core collapses. It goes from Earth-sized to city-sized. Neutrinos come out with a flood of energy, and the inner part of the star is now collapsing. The remaining gas is collapsing down. This collision produces an outgoing shock wave that ripples through the star and blows it away. It reaches the surface in just a few hours. The visible result is a supernova explosion.

- Most supernovas leave behind tiny, dense, neutron-rich cores. These neutron stars typically have masses of about 1.5 solar masses and diameters of about 25 kilometers. A teaspoonful would weigh 1 billion tons on Earth.

- Such a core-collapse, or Type II, supernova can achieve a luminosity of up to 1 billion Suns at maximum brightness. They rise to this maximum within a few days, and then they fade slowly over subsequent weeks and months.

- Hundreds of supernovas are seen in other galaxies every year. The nearby galaxy M51 has had two since 2005. Supernovas stand out even at distances of many millions of years. Their rarity indicates that there is a Milky Way Type II supernova every 100 years. The last one widely seen on Earth was in 1604.

Eta Carinae

- As one of the most massive evolved stars in the Milky Way, Eta Carinae is a leading candidate to be our next supernova. It is a prototypical example of a luminous blue variable (LBV) star. Such blue supergiants are not only large, massive, and luminous, but they also can undergo dramatic variations in brightness that are extreme enough to almost mimic a supernova.

- LBV stars are rare. Only about 20 are known in the Milky Way. The Pistol Star is an LBV that is located near the galactic center. Its near-infrared Hubble image reveals expanding gas shells. This is indicative of giant eruptions 4000 and 6000 years ago. It lost about 10 of its over 100 solar masses in these events.

- At 7500 light-years away, Eta Carinae is closer to Earth than the Pistol Star. And with much less dust, it is easily studied at optical wavelengths. It was first catalogued in 1677. At this time, it had a rather modest naked-eye brightness. By the 1700s it became one of the brightest stars in the whole constellation Carinae. By 1843, it was the second brightest star in the sky. At that time, it reached its peak luminosity of about 30 million Suns. By the 1860s, it faded below naked-eye view. It then became naked-eye again in the 1950s and continues brightening.

- The first evidence that Eta Carinae was more than a simple point source came from a ground-based image in 1945. Subsequent images over the years showed an expansion in its associated Homunculus Nebula. Imaging this nebula in detail was a key goal of Hubble when it was launched. With Hubble, we could apply observations in terms of resolution down to scales of about 0.05 of an arc second. This resolution shows expanding bipolar lobes of dust and gas that enshroud Eta Carinae.

- An instrument on board the telescope called the Space Telescope Imaging Spectrograph allows us to take spectra of objects across the nebula. This indicates that lobes are expanding over 600 kilometers per second. Lobe size and expansion velocity are consistent with its

1843 outburst. Abundances indicate that several solar masses were ejected in 1843. Eta Carinae is currently losing 0.001 solar masses per year.

- Among the many questions posed by the Hubble observations and others are why is Eta Carinae losing so much mass, and why was the 1843 outburst bipolar? LBV stars like Eta Carinae that have masses well over 100 solar masses have very strong stellar winds. Their hot fusion cores produce huge amounts of energy—so much energy that the energy itself exerts a radiation pressure on the gas. How pressure build-up can lead to outbursts is not clear.

- Bipolar outflow patterns are not unusual in astronomy. Some planetary nebula, such as Hubble 5, exhibit such structure. Perhaps this kind of bipolar structure is due to the magnetic field of the white dwarf star, or it is possible that the gravity field has a companion star. Many ideas have been offered to explain Eta Carinae's bipolar lobes, ranging from its asymmetric burst to the notion of a circumstellar disk around Eta Carinae.

- In addition, there is strong evidence that Eta Car is a binary object. Its spectral and light curve variations show a 5.5-year periodicity. This indicates that Eta Carinae is actually a binary of a 30-solar-mass star and that the main body is a 100-solar-mass star. They're orbiting around each other at a distance of about 15 astronomical units. This notion is unresolvable due to obscuration, even in the Hubble image.

- The space telescope Chandra took an X-ray image that reveals an outer ring of hot gas around the bipolar outflow. A 2-light-year-diameter ring suggests that there was another outburst in Eta Carinae over 1000 years ago. The reason it's shining so brightly now in X-rays is perhaps because it's being heated by some of the high-velocity gas from the 1843 outburst slamming into it.

- Interestingly, it is possible to better understand Eta Carinae through observations of the 1843 outburst itself. We can effectively go back

in time to study such an explosive event through a phenomenon known as a light echo. Recall the Pleiades reflection nebula, in which the dust grains near the stars reflect their light. The brightest patches are located a few light-years from the stars. Thus, the nebula light is about a year older than the starlight. The starlight among the stars in the Pleiades is more or less constant, so the nebular light is more or less constant.

- In terms of brightness, the Eta Carinae 1843 outburst has been considered the prototype for a class of very luminous extragalactic outbursts known as "supernova impostors," which reach peak brightnesses similar to faint supernovas, but the star remains after the subsequent fade. They typically exhibit outburst spectra similar to that of LBVs.

- How are Eta Carinae, LBVs, and supernova impostor outbursts linked? This question provides great motivation to improve our understanding of this kind of linkage. Perhaps we can better predict the timing of Eta Carinae's explosion into a supernova. Is it years or hundreds of thousands of years in the future?

Suggested Reading

Kaler, *The Hundred Greatest Stars*.

Mazure and Basa, *Exploding Superstars*.

Wheeler, *Cosmic Catastrophes*.

Questions to Consider

1. Is it possible that there may have been galactic supernovas over the past several hundred years that went unobserved by anyone on Earth?

2. What will happen to Eta Carinae's binary companion star when Eta Carinae explodes as a supernova?

Runaway Star, Zeta Ophiuchi

Lecture 11

Because the lifetimes of O stars are so short, we don't expect to find one far from the gas cloud or star cluster in which it was born. However, 15 degrees north of Antares, Scorpius's bright red supergiant, is a very bright O star named Zeta Ophiuchi in splendid isolation. A beautiful clue to its origin can be found in an infrared image obtained with the Spitzer Space Telescope. Based on its age and the velocity and direction of its motion, the star was born as a member of the Upper Scorpius cluster located in Antares.

Runaway Stars

- The primary component to the motion of most of the stars and gas clouds in the disk of the Milky Way is the rotation of the Galaxy. Because the Sun participates in this motion, it is important to recognize that the measurement of velocity is a relative one and is usually referenced to the Sun or the galactic center or a group of nearby stars collectively defined as the local standard of rest (LSR).

- The Sun is orbiting the galactic center at an average velocity of about 240 kilometers per second. The Sun is moving about 10 kilometers per second relative to the LSR. This velocity is typically called a "peculiar velocity." The Sun's peculiar velocity is quite typical for other stars and gas clouds in the disk of the Milky Way.

- Closer to home, Earth rotates at about 1 kilometer per second. The Earth orbits the Sun at 30 kilometers per second. Indeed, at its distance from the galactic center, with its velocity of over 200 times the speed of a rifle bullet, it still takes the Sun 200 million years to make a single orbit around the galactic center.

- In comparison to the Sun and its peculiar velocity of about 10 kilometers per second with respect to the stars in its neighborhood, runaway stars are defined as those stars that have peculiar velocities

measured in tens to over a hundred kilometers per second. About 15 percent of O and B types of stars are runaway stars. Many appear to be moving away from star clusters.

- Among this group of high-velocity runaway stars, a few stars are found with peculiar motions of over 300 kilometers per second. At these kinds of velocities, it's possible for a star to actually escape the gravitational field of the galaxy. These so-called hypervelocity stars can fly away off into extragalactic space. Most of these hypervelocity stars appear to be coming from the vicinity of the galactic center region.

- So how do we measure the space velocity of a star? We typically break the velocity down into its two component parts: the transverse component across our line of sight and the radial component along our sight line. These two components require different types of measurements.

- The transverse velocity is measured by a star's proper motion, which is the angular motion a star makes across the sky over time. This is, for almost every star, a very tiny amount. The typical units we measure proper motion in are milliarc seconds per year. Even for the nearest stars, even though they're moving quite fast, the proper motions are very small. How can peculiar velocities of 10 kilometers per second lead to such tiny proper motions? The simple answer is because the stars are so far away.

- In the case of stellar proper motions, let's consider a real grouping of stars in the sky: the Big Dipper. Bright stars form and deform the Big Dipper's shape over 200,000 years. Small proper motions are why constellations last so long.

- Like parallax, personal motions are difficult to measure for distant stars. Also, you need to know distance to the star to convert personal motions to transverse velocity. Thus, this particular velocity component, the transverse velocity component, is typically the most difficult to measure in stars in the galaxy.

- Measuring the radial velocity of a star through the Doppler effect is easy to do, provided that the star is bright enough and that we've got a telescope big enough with a good spectrograph. The Doppler effect tells us that if the star is moving toward us, the wavelengths of light get shorter and, therefore, bluer. If the star is moving away from us, the wavelengths of light get stretched, shifting to redder wavelengths. The amount of the wavelength shift is proportional to its velocity, so the blueshift and redshift of lines give velocity and direction.

Ursa Major, also known as the Big Dipper, is a grouping of stars in the northern sky.

- In the case of the nearest star system, Alpha Centauri, that star exhibits a relatively large proper motion of 3.9 arc seconds per year. It's also the nearest star, at a distance of 1.3 parsecs, or 4.3 light-years. Putting these numbers together, we can determine that the transverse velocity of Alpha Centauri is 24 kilometers per second.

- The Doppler effect gives us the radial velocity of Alpha Centauri. The spectrum of Alpha Centauri—and we interpret that in terms of the Doppler effect—tells us that the radial velocity of the star is 20 kilometers per second toward us. Together, they indicate that Alpha Centauri has a true space velocity of 31 kilometers per second.

- The determination of both of these velocity components has been particularly important in understanding the hypervelocity star HE 0437-5439. This B star has a radial velocity of 720 kilometers

per second away from the Sun. Based on its spectral type and measured brightness, we can infer that its distance is about 200,000 light-years. It's just 16 degrees on the sky away from the Large Magellanic Cloud, which is a satellite galaxy of the Milky Way at a distance of about 160,000 light-years.

- Was this hypervelocity star HE 0437-5439 ejected from the Milky Way or from the Large Magellanic Cloud? Only Hubble can measure the proper motion of such a distant star. Astronomers used comparisons of high-resolution images of this star taken about 3.5 years apart to determine that this star has a proper motion. It's less than a milliarc second per year, but they have enough of a measurement to determine its direction: This hypervelocity star is moving away from the Milky Way's galactic center at a velocity of about 550 kilometers per second.

- Given the position of the star on the sky and its distance, it indicates that this star has been flying out from the galaxy for about 100 million years. That's a bit of a puzzle, because this start is a B star, and B stars typically have main-sequence lifetimes on the order of about 20 million years.

- The explanation that astronomers have come up with is that originally this particular star was part of a triple-star system including a close binary star—two stars orbiting really close to each other and another one orbiting around them. What happened is this triple system came very close to the 4 million-solar-mass black hole at our galactic center. The black hole captured the outer star in the triple system in orbit and kicked the binary away through gravitational interaction at high velocity out of the galaxy.

- As this star flew away off into space beyond the Milky Way, the more massive one of this pair of stars would have evolved off the main sequence first. As it got bloated and got bigger, the other star actually merged with it into a single star. It basically rejuvenated the one that was getting old and created a new star, sometimes called a blue straggler, which has all the characteristics of a blue

B star. These gravitational encounters between binaries or triples and black holes can be gravity-simulated with computers. Such encounters can produce hypervelocity stars with speeds up to 1000 kilometers per second.

- Binary encounters with massive stars rather than a black hole could explain some of the observed runaway stars. A good example involves the Large Magellanic Cloud, which is a gas-rich star-forming irregular galaxy. If we look closely into the Large Magellanic Cloud, we see a very exciting nebula where there's an active starburst going on—all kinds of star formation. This nebula, called 30 Doradus, is about 650 light-years wide. At its core is a young, massive star cluster called R136.

- In a deep optical image of 30 Doradus, you find a 90-solar-mass runaway star that's 375 light-years away from R136. We can glean its direction from a Hubble view of its nebular interaction, and it appears to be moving away from R136 at about 100 kilometers per second. It turns out that this star could have gone these 375 light-years in a travel time of about a million years. That's less than the main-sequence lifetime of this kind of star.

- Perhaps this runaway was once part of a massive binary in R136. It's possible that a more massive star interacted with the binary and that the runaway got kicked out of the binary and cluster by gravity, leaving behind a new binary. These kinds of interactions can eject runaways up to velocities of hundreds of kilometers per second.

Zeta Ophiuchi

- In the case of Zeta Ophiuchi, an optical image alone gives no hint that it is a runaway star. All that appears in this sky region are stars amidst a very faint gaseous nebula. The corresponding infrared image of Zeta Ophiuchi provided by Spitzer shows filamentary wisps of glowing dust and gas in a graceful arc around the star. This is called a bow shock. The bow shock is especially evident in the warm dust.

- Zeta Ophiuchi, a runaway star, is moving at high speed through a nebula. As it runs through the gas and dust in the nebula, it's compressing and heating due to the high star velocity of Zeta Ophiuchi, plus Zeta Ophiuchi's intense stellar wind pushing on this gas and dust.

- The infrared bow shocks of many runaway stars have been revealed at lower resolution through images obtained with the Wide-Field Infrared Survey Explorer (WISE) satellite observatory.

- What about Zeta Ophiuchi? How did it become a runaway from the bright stars and glowing clouds of the young Upper Scorpius cluster? Was it once part of a cluster binary that was disrupted by a collision with another star? Actually, there is another binary possibility. What if its companion blew up as a supernova?

- Various binary supernova cases have been simulated. Given the current position of Zeta Ophiuchi and its 35 kilometers per second motion away from Upper Scorpius, it was part of the cluster about a million years ago. If a corresponding runaway neutron star could be found whose motion puts it in the cluster near Zeta Ophiuchi at that time, then a supernova origin would be quite likely.

Suggested Reading

Kaler, *Extreme Stars*.

Pasachoff and Filippenko, *Cosmos*.

Waller, *The Milky Way*.

Questions to Consider

1. Are runaway stars serious threats to disrupt the planetary orbits in the solar system? Why or why not?

2. Imagine a binary star system consisting of two solar-type stars. Would the evolution of this system eventually lead to the production of a runaway star?

The Center of the Milky Way

Lecture 12

Since the 1970s, a series of increasingly sensitive ground- and space-based observations have revealed the galactic center region to be like nowhere else in the Milky Way Galaxy. One of the most striking views is a recent composite of Hubble near-infrared, Spitzer infrared, and Chandra X-ray images across the central 250 light-years of the Milky Way. It shows pervasive clouds of very hot gas and a complex variety of nebular structures shaped by supernovas, massive stellar winds, and a 4-million-solar-mass black hole at its heart.

The Galactic Center of the Milky Way

- Unlike the Earth, which we can study from a variety of vantage points, the Galaxy is so large that our view is limited to just one perspective, and that view is from inside the Galaxy itself. Nevertheless, through a variety of multiwavelength observations and studies of other galaxies, we have pieced together a global picture of the Milky Way and our location within it.

- At optical wavelengths, our view of the Galaxy is clearest above and below the galactic disk through the galactic halo. Although sparsely populated with stars and interstellar matter, the halo is home to about 170 globular star clusters.

- A typical globular cluster has about 100,000 stars and is about 100 light-years in diameter. These dense spherical star fields are great Hubble targets. They are much richer and older than disk open clusters. An H–R diagram of a typical globular cluster shows that these clusters have ages over 10 billion years. Amazingly, it is these clusters that pinpoint the galactic center.

- At radio wavelengths, we can directly observe the galactic center region inferred from the globular cluster distribution. The most powerful tool in this effort has been the Very Large Array (VLA)

telescope in New Mexico. It consists of 27 dishes that are each about 25 meters in diameter and are arranged in a Y-shaped array. The baseline is adjustable up to 36 kilometers. The interferometer acts as a single baseline-sized dish. The angular resolution you get with a telescope on the sky is proportional to the wavelength that you're observing divided by the baseline, or the size of your telescope.

- Our first zoomed-in view with the VLA is a wide-field view of the central 1800 light-years of the galactic center at 6-light-year resolution. In this image, we see a variety of structures along a diagonal. These structures along this diagonal define the galactic plane. The emission at radio wavelengths is being produced by high-velocity electrons moving in ionized gas. Some of this ionized gas is associated with star formations, such as Sagittarius B2 and Sagittarius B1 in this image.

- You can also get emission from electrons and ionized gas spiraling along magnetic field lines. Often, we see this associated with supernova remnants and filamentary structures. Separating out the ionized gas, the electrons flying through ionized gas and emitting radiation, and then spiraling along magnetic field lines, we can figure out which is which by looking at the spectra of this emission.

- The galactic center is in the Sagittarius A region. There are two large components to the Sagittarius A emission south of the filaments. Sagittarius A East is a 30-light-year-wide supernova remnant. Sagittarius A West is a mini-spiral of ionized gas, and that's where the heart of the galactic center is. The gas is ionized by hot, massive stars in the central parsec around the galactic center. The gas and stars in this region orbit a compact radio source called Sagittarius A*, which is located at the dynamical galactic center of our Galaxy.

- At near-infrared wavelengths, the orbits of the massive stars near the galactic center can be studied with large ground-based telescopes. The motivation for such observations is to determine the mass of Sagittarius A* and determine if it is indeed a supermassive black hole.

- The Keck 10-meter telescopes on Mauna Kea on the island of Hawaii have been key because they allow us to look at faint objects. They achieve sky resolutions of about 0.05 of an arc second through adaptive optics technology. They use laser guide stars to correct for the turbulence as the light goes through the atmosphere.

- With this sharp near-infrared imaging, we find that the central light-year of our Galaxy has hundreds of stars in it. This is amazing. Recall that the distance between the Sun and Alpha Centauri is 4.3 light-years. So, we have to go 4.3 light-years to find the nearest star, and in the galactic center region in that inner light-year, there are hundreds of stars. Many of these stars are very young. They have ages less than 10 million years. Their origin is unclear.

- The central 1 arc second around the galactic center corresponds to a size of only about 0.1 of a light-year, or 8000 astronomical units. With the Keck Telescope and other telescopes, the positions of these stars have been monitored since 1995, getting very accurate measurements to see if they move. Some clearly show orbital motion around the Sagittarius A* position.

- The motions of these stars tell us there's something enormously massive at the Sagittarius A* position. Indeed, a complete orbit has actually been observed for a star called SO-2, with a period of 16 years, and a fainter star called SO-102, with a period of 11.5 years around the galactic center. The latter star, SO-102, at its closest approach to Sagittarius A*, is just 260 astronomical units. The orbital velocity of this star is 5000 kilometers per second.

- Based on the motions of these stars, this object Sagittarius A* has about 4 million solar masses inside a radius of just 20 astronomical units. That's twice the distance between the Earth and Saturn. Only a black hole could pack that much mass in such a space. In the case of a 4-million-solar-mass black hole, such an object has an event horizon with a radius of about 0.1 of an astronomical unit.

- The event horizon around a black hole defines the distance from the black hole where the escape velocity is greater than the speed of light. Nothing at that radius or closer can escape the black hole, because nothing can go faster than the speed of light. Such a thing has enormous gravity. A star that passes really close to the black hole at the galactic center could be tidally disrupted, and the infalling matter would basically create a glowing disk of material around that black hole called an accretion disk.

- Sagittarius A* is faint in the near-infrared with modest, short bursts, but there's no evidence that it has eaten a star recently. That's aligned with our expectations, because we expect, based on the stellar density at the galactic center, that you wouldn't get a disruption event where a black hole would rip a star apart through tidal effects. That should happen only about once every 100,000 years.

Evidence for a Supermassive Black Hole

- The ground-based evidence for a supermassive black hole and other phenomena at the galactic center have made it a primary target for space observations. In particular, the Chandra X-ray Observatory has provided a pioneering high-resolution view of high-energy sources and hot gas in this region.

- Chandra was launched in 1999 on the shuttle *Columbia*. When the shuttle went off, it went off not only with Chandra, but also with a rocket to boost it into higher orbit around the Earth. At the time, this constituted the heaviest payload ever launched on the space shuttle.

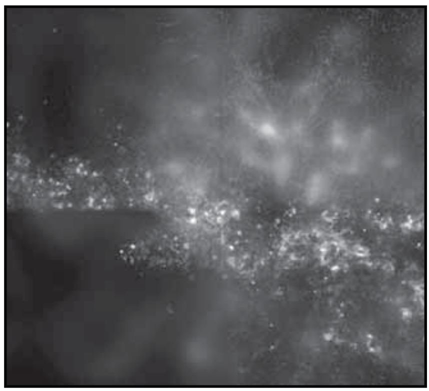
- Chandra is similar in size to Hubble. Chandra focuses X-ray light with low-incident angle mirrors. High-energy photons, like X-rays, would be absorbed by a typical mirror. With low-incident angle mirrors, the photons graze off these nested mirrors, and that's how they're focused with the Chandra telescope. These nested mirrors are range in size up to 1.2 meters. They provide 1 degree of field of view at 0.5 arc seconds of resolution. This is 8 times better resolution than any previous X-ray telescope. It can also detect 20 times fainter sources than before.

- A considerable amount of time has been spent focusing on Sagittarius A* itself. Chandra has discovered X-ray flares from Sagittarius A*. Typically, they occur once a day and have a duration of a few hours, and the object increases in brightness by about a factor of 10. They're not as common as the shorter, more modest infrared flares. However, typically an infrared flare accompanies an X-ray flare.

- It's not yet clear what's causing these flares. An effort continues to compare these flares at various wavelengths. One idea is that they could be due to asteroids.

- On a larger scale surrounding Sagittarius A*, Chandra has revealed widespread diffuse X-ray emission indicative of hot gas and a number of point sources corresponding to hot, massive stars. The hot gas indicates a very turbulent interstellar medium in this region. It's heated by a supernova explosion, vigorous stellar winds, and the Sagittarius A* itself. This is not the ideal medium for star formation. However, we see all these very young stars with ages indicative that they formed less than 10 million years ago.

- Where did the massive stars around Sagittarius A* come from? One idea is that perhaps there's a giant gas accretion disk around Sagittarius A*. It's less likely that a young cluster, or somehow a cluster of stars, migrated to Sagittarius A*. There's no evidence of many corresponding low-mass stars.



The Chandra X-ray Observatory has provided high-resolution views of gamma-ray bursts.

- On an even larger scale, the Chandra data shows that the diffuse X-ray emission is prominent over much of the inner 500 light-years of the Milky Way. In a Chandra image, we see that the Sagittarius A region itself has lots of high-energy emission from hot gas, and particularly we see diffuse X-ray emission north and south of Sagittarius A*, perhaps indicative of an outflow of hot gas from this particular object. There's also hot gas throughout this region. We expect that there have been supernova explosions and associated remnants, and massive stars are everywhere in this region.

- Another way to get a view of this is to look at this region with other space telescopes—specifically, with Spitzer and with the Hubble Space Telescope. Astronomers have compared what the central part of the galaxy looks like by comparing both these Chandra X-ray images to Spitzer infrared and Hubble near-infrared, and they have surveyed this central 250 light-year region.

- Spitzer observations are particularly suited through its infrared view looking for heated dust. In the case of Hubble, you get a very high-resolution view in the near-infrared that gives us some indication of the nebular structure—what the gas is doing. When you put all of this together, you get a composite of the Chandra, Spitzer, and Hubble observations. There are many features in the composite image beyond Sagittarius A*, including the Quintuplet cluster, the Arches cluster, and the Arc Filaments.

- Indeed, with its widespread hot gas, high massive-star density, and supermassive black hole, the galactic center is the most exotic region of the Galaxy. A clue to the extent that its phenomena might be related was recently provided by another space observatory: the Fermi Gamma-Ray Telescope. Through its observations, it revealed two huge gamma-ray bubbles rising north and sinking south from the galactic center. The total length of this structure is 50,000 light-years.

- Perhaps these are due to the outflows of galactic center starbursts. Perhaps in the recent past, there was a huge infall of mass on the black hole at our galactic center and that led to an outflow event.

Perhaps it's not just these massive stars around the galactic center in these clusters. Perhaps the black hole itself is driving these big, high-energy lobes. Central supermassive black holes are common in other galaxies. And some show polar outflows.

Suggested Reading

Melia, *The Black Hole at the Center of the Galaxy*.

Scharf, *Gravity's Engines*.

Weaver, *The Violent Universe*.

Questions to Consider

1. Describe the night sky as viewed from a planet around a star in the Arches cluster.

2. Contrast the patterns of star formation at the galactic center with those in the Swan Nebula. What could explain the differences?

The Andromeda Galaxy

Lecture 13

Space observations of Andromeda have been vital not only in telling us where its going in terms of its motion, but also where its been in terms of its recent star-formation history. The ringlike disk distribution of young hot stars and dust clouds revealed by GALEX and Spitzer is not readily apparent at optical wavelengths from the ground. It is a key clue that some of the star formation in Andromeda has been triggered by a galaxy collision in the recent past. Such collisions and other unusual factors can alter the appearance of spiral galaxies far beyond the case of Andromeda.

GALEX

- Andromeda and the other galaxies are not distributed randomly across the sky. They are typically found in clusters held together by their mutual gravity. These galaxy clusters range in size from small groups to rich 1000-member associations.

- The Milky Way, Andromeda, and more than 50 other nearby galaxies form a cluster that was named the Local Group by Edwin Hubble. Its members stretch across about 10 million years of space. The inter–Local Group space is vaster and emptier than the interstellar medium in the Milky Way. The space between the clusters of galaxies is even more vast and empty. Indeed, the universe is mostly empty space.

- The Milky Way and Andromeda (M31) within the Local Group are, by far, the two most massive galaxies. With a diameter of more than 200,000 light-years, M31 is larger than the Milky Way. There is a distance of 2.5 million light-years between the Milky Way and M31.

- The Triangulum Galaxy (M33) is the only other Local Group spiral. Its diameter is about half that of the Milky Way. The other Local Group galaxies are small irregulars and dwarf ellipticals. Most of

The Andromeda Galaxy, the nearest large galaxy, is one of the few galaxies that is visible to the naked eye.

these smaller galaxies are satellites of the Milky Way and M31. And M33 itself may be a satellite of M31.

- The evolution of galaxies in the Local Group and beyond is strongly tied to their rate of star formation. Ultraviolet images of galaxies provide an excellent measure of the rates and locations of star formation because the hot O and B stars that lead the shortest lives on the main sequence are the most luminous stars in the ultraviolet. In other words, two galaxies of similar brightness in the optical can look quite different in the ultraviolet if one has undergone a significant burst of star formation over the past few hundred million years and the other has not. The Galaxy Evolution Explorer (GALEX) satellite observatory was launched in 2003 to study the ultraviolet evolution of galaxies over the past 10 billion years.

- A key feature is its large field of view. It is over twice as wide as a full moon. It can observe many distant galaxies at a time. For a really big galaxy on the sky, like M31 or Andromeda, you only need a few pointings to cover it. Hubble's ultraviolet field of view has a diameter that is 0.5 percent of GALEX. That means that Hubble would need about 100,000 pointings to image M31.

- GALEX's large field of view is due to its small 0.5-meter mirror. With that mirror size, it has reasonable resolution, but certainly not as high resolution as with Hubble. The imaging resolution for GALEX is about 5 arc seconds. It does this imaging basically with two wide wavelength bands in the ultraviolet. The far-ultraviolet band is centered at about 150 nanometers, and that's the best band for looking at the hottest stars. The near-ultraviolet band, centered at 230 nanometers, is best for looking at somewhat cooler but still rather hot stars.

- Putting together the optics in this package, it's actually quite a small spacecraft. You can put this kind of technology together to do this kind of work with just a small spacecraft. Indeed, GALEX weighs only about 280 kilograms. With the solar panels unfurled, the whole spacecraft is about 2 meters tall by 3 meters wide. Due to its small size, it was launchable with a Pegasus rocket off an airplane. GALEX could be squeezed and fit into a tiny space about 1.1 meters wide within the nose cone of this rocket.

- So, GALEX is attached to the nose cone of the Pegasus rocket. Then, the rocket is attached to the belly of an L-1011 jumbo jet. The jet takes off, goes up to about 40,000 feet, and then drops the rocket. The rocket engines fire, and then about 10 minutes later, GALEX is in orbit around the Earth.

- Pegasus works great for payloads that are smaller than about 450 kilograms. The advantage of this is that Pegasus is much cheaper to launch probes and observatories into space than large ground rockets, which need a lot more fuel to get it off the ground out into orbit.

- GALEX was launched specifically into a low-Earth orbit at an altitude of about 700 kilometers. Until its recent decommissioning in 2013, it surveyed the extragalactic sky above and below the plane of our Galaxy. It has measured the star-formation rates in millions of galaxies. The total cost of this mission was about 150 million dollars, which is a relatively low cost.

When Two Galaxies Collide

- As the closest spiral galaxies to the Milky Way, Triangulum and Andromeda have been observed in greater detail with GALEX than any other spiral. This level of detail allows for excellent comparisons of their ultraviolet indications of star formation with those at other wavelengths.

- In the case of Triangulum, a deep wide-field optical image reveals a small nucleus with loosely wound spiral arms. The ongoing star formation in the spiral arms is delineated by the blue light of young hot stars and the pinkish patches of emission nebulas heated by those stars.

- Hubble has imaged the brightest pink area in M33, which is associated with one of the largest star-formation regions in the Local Group. This gaseous nebula is called NGC 604. It is 1500 light-years across. At its heart, it has a 3-million-year-old star cluster that includes over 200 O stars.

- On the larger scale, GALEX can look at the whole of M33, and it can trace these arms we see at optical wavelengths and study what they look like in the ultraviolet. There is a GALEX image that is a composite of both the far-ultraviolet and near-ultraviolet bands.

- In addition to GALEX observations of M33 looking at the ultraviolet, Spitzer can also give us some information about the infrared in terms of its dust comparisons. There are many regions where the dust is so dense that it blocks the ultraviolet starlight. In other regions, like NGC 604, the ultraviolet is very bright because there's a little bit less dust in that particular region.

- In the case of the Andromeda Galaxy, a deep wide-field optical image reveals a larger nucleus and more tightly wound spiral arms than M33. Older stars make the nuclear region look yellowish. Because Andromeda is inclined much more than M33, its spiral pattern is less obvious at optical wavelengths. It's actually inclined by an angle of 77 degrees to our line of sight.

- The most evidence of this spiral pattern is in the inner arms; it seems to be more obvious in terms of the dust lanes. The outer arms of Andromeda are where you see more of the blue stars and the more reddish-pinkish nebulas associated with those blue stars.

- It's also important to note Andromeda's dwarf satellites nearby—M32 (above the disk) and M110 (below the disk). Such dwarfs are typically made of old stars, and they typically have little interstellar matter in them. M32 is about 7000 light-years across, and it has a mass of about 0.5 percent of M31's. A close-up of M110 reveals a couple of dust clouds. Also, there is some evidence that there was recent star formation that went on in this particular dwarf elliptical. M110 is just a little bit larger and fainter than M32.

- Hubble has imaged the central 35 light-years of M31 at high resolution. It reveals an about 200-million-year-old central cluster of blue stars. Also evident around this cluster of blue stars is an outer ring of older red stars. Spectroscopic data of these stars and determination of their velocities based on those velocities indicates that these stars are orbiting an object at the center—essentially a black hole that has a mass on the order of 100 million solar masses.

- What could have caused a burst of star formation near Andromeda's central black hole about 200 million years ago? We have asked a similar question regarding the even younger stars near the Milky Way's central black hole.

- In the case of M31, Spitzer and GALEX have provided a clue. This clue begins if we compare optical images of M31 and the 8-micron Spitzer image of M31. The Spitzer view shows that the dust does

not exhibit a classical spiral pattern in Andromeda. There appears to be an inner ring and an outer ring. A typical spiral shouldn't have this kind of structure. Astronomers have been able to model this kind of structure with the idea that the small dwarf elliptical M32 actually collided with Andromeda some 200 million years ago. That collision may have stimulated star formation at the core of M31.

- This non-spiral structure in Andromeda is also evident in the GALEX images. The observations from the GALEX images in the ultraviolet along with the Spitzer images in the infrared are consistent with a collision scenario, and that was not apparent from optical observations.

- Besides the M32 scenario, there is considerable evidence that both M31 and the Milky Way have interacted with their small satellite galaxies in the past and indeed have absorbed some. Despite their huge 2.5-million-light-year separation, is it possible that these two large spirals could also eventually collide? Based on information from Hubble, it does indeed look like Andromeda will make a head-on or nearly head-on collision with the Milky Way in the future.

- The collision of two massive galaxies each with hundreds of billions of stars, vast amounts of interstellar gas and dust, and a supermassive black hole is difficult to imagine. Fortunately, such complicated interactions can now be modeled using high-speed computers and sophisticated software that takes into account the effects of gravity, gas flows, and collision-induced star formation.

- What these models show us is that over the next 4 billion years, Andromeda will slowly approach the Milky Way Galaxy. The act of both galaxies first passing by each other will lead to tidal tails of gas and stars being ripped from both galaxies and thrown off into extragalactic space. The collisions between these two galaxies will actually lead to very, very few, if any, star-on-star collisions, because the space between the stars on average in these galaxies is vast.

- The gravity associated with all of these stars would have amazing effects on stirring up stars and sending them all over the place. As this dance continues, the two galaxies would go through basically a dance, passing closer and closer over the following 3 billion years. Eventually, the two galaxies will merge into what essentially will be gas-free elliptical galaxies. Some gas would be tidally expelled into intergalactic space, and some would be collision-shocked into a starburst.

Suggested Reading

Rich, "Galaxies Seen in a New Light."

Van Den Bergh, *The Galaxies of the Local Group*.

Villard, "Skyfire."

Questions to Consider

1. Is it likely that the Local Group included another large spiral galaxy like Andromeda or the Milky Way billions of years ago? Why or why not?

2. Why is it unlikely that the solar system will be ripped apart when the Milky Way and Andromeda collide?

Hubble’s Galaxy Zoo

Lecture 14

The Hubble Space Telescope has focused its sharp eye on some of the most unusual looking galaxies in the local universe. Many of these peculiar cases can be understood in terms of geometrical effects, starbursts, and gravitational interactions with other galaxies. With its ring of blue young stars circling a yellow nucleus of older stars, Hoag’s Object is the most photogenic example of a celestial rarity known as a ring galaxy. Although ring galaxies are often understood as the result of a collision between a small galaxy and a large spiral, the beautiful symmetry of Hoag’s Object is a fascinating puzzle due to the conspicuous absence of a collision partner.

The Appearance of Galaxies

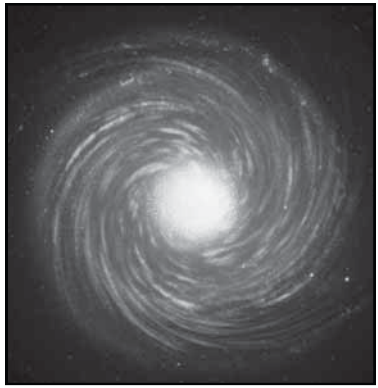
- The appearance of galaxies on the sky is a function of many factors, including their physical size, distance, intrinsic shape, and inclination. The foundation for understanding these factors was largely established by Edwin Hubble. Through this work, he became the most famous astronomer of the 20th century. It is particularly fitting that the sharpest images of the extragalactic universe are being taken with the telescope that bears his name.

- With the Mt. Wilson 100-inch telescope, Hubble looked at Andromeda and figured out a way to get the distances to some of those stars. At the same time, Hubble was studying spiral nebulas, and some had elliptical symmetry. Hubble used the Mt. Wilson to accumulate unprecedented photos of many galaxies. Using his photos, Hubble developed what we now call the tuning fork classification scheme, which is a way to separate out different kinds of galaxies.

- Hubble found that within about 100 million light-years, about 90 percent of the galaxies are either ellipticals or spirals. The rest are lumped in kind of an irregular morphology classification. The ellipticals are typically gas-poor systems of old stars. All of their

stars are very old—10 billion years old or more—and it appears that all of the stars in these galaxies formed at one time. These elliptical galaxies range in shape. Some are very circular (classified as E0s), and some are very elongated and cigar-like (E7s).

- The spiral galaxies are disks, and they're gas-rich systems of both old and young stars. In spiral galaxies, spiral stars form continuously over the past 10 billion years. Hubble classified the spirals by the shapes and sizes of the central bulges of these spirals. He noted that about half of the spirals have a bar-shaped bulge. The origin of these bars is still unclear. It may be an evolutionary stage in the evolution of many large spiral galaxies.



Spiral galaxies, named for their spiral structure, can be classified as either normal or barred spirals.

- The optical cameras onboard the Hubble Space Telescope are capable of imaging galaxies with an angular resolution of 0.05 arc seconds. This resolution is about a factor of 10 better than that typically possible with the largest ground-based telescopes. It means that Hubble can resolve out comparable galaxy structures at distances 10 times greater than that from the ground.

- In generally, galaxy images give no more than crude distance information. If you want to get the distances to galaxies, you've got to rely on Edwin Hubble's most famous achievement. In 1929, he found this amazing linear relationship between the distance of a galaxy and its radial velocity. Today, we call this Hubble's law. It tells us that as we look at galaxies that are farther and farther away, they're moving away from us faster and faster. Indeed, essentially all the galaxies beyond the Local Group exhibit redshifts.

- The simplest interpretation of these observations is that the universe is expanding. No matter which cluster of galaxies you call home, as you look out into space and as the universe expands, all the other galaxies will appear to move away from you. The galaxies that are farther away from you will move even faster away from you. The longer the distance—the longer the photon travel time—the more that their wavelengths will be stretched by the expanding universe and the higher the redshift velocity measured on Earth.

Peculiar Cases in the Galaxy Zoo

- Now that we've covered a bit of the basics about galaxies, let's try to interpret some of the more peculiar cases in Hubble's galaxy zoo. The first class of curiosities involves geometrical effects due to special observer-dependent views. In other words, these cases might not look as peculiar if viewed from a galaxy with a different vantage point.

- The galaxy NGC 3314 appears to have two different sets of spiral arms. Is this actually a collision between two spiral galaxies? That can't be, because when spiral galaxies collide, you see tidal tails. And we don't see any evidence of tidal tails in an image of NGC 3314. What's going on here is actually just a chance grouping, where one spiral, the face-on spiral, is just in front of the inclined one.

- Applying Hubble's law, we get that the face-on galaxy is at a distance of 117 million light-years, and the more distant inclined galaxy is at a distance of 140 million light-years. They're over 20 million light-years apart; they're not interacting. It's just a matter of perspective. This perspective issue is particularly key with spiral galaxies.

- There is a face-on Hubble image of the spiral M101, sometimes called the Pinwheel Galaxy. It is twice the diameter of the Milky Way, and it's at a distance of 25 million light-years. In the image, we see the familiar spiral arms in the dust, and we also see young stars. How thick is this galaxy? It's not that obvious from a face-on perspective. But if you look closely at the Pinwheel image and focus on the 10:30 position on a clock in this image near the edge of

the arms, you can see that the dust is actually thin enough to see a distant barred spiral galaxy.

- In terms of spiral galaxies, you can use the angular size as a very crude gauge of distance. The reason you can do it very crudely is that spiral galaxies typically are within a factor of a few the physical size of the Milky Way Galaxy. You really can't do that with elliptical galaxies, though, because ellipticals have a much greater range in their sizes—a factor of 1000. Also, with an elliptical, they often look similar from different perspectives.

- Such is not the case for another one of the galaxies in the zoo, the 45-million-light-year distant Spindle Galaxy. It has an extended halo of stars that make it look like an elliptical galaxy. However, its thin dust lane, which is less than 1000 light-years across, indicates an edge-on disk. This galaxy seems to have characteristics both of an elliptical galaxy and a spiral galaxy, which is called a lenticular galaxy (S0). It's an elliptical-spiral hybrid.

- In the case of this galaxy, we don't know its exact spiral pattern, because we're seeing it on the edge. Nevertheless, we see characteristics on the edge that are characteristic with other spirals, such as the red bulge around the bright nucleus and the blue stars along the disk. A close-up also reveals little dust filaments rising from the disk. The dust is being lifted through stellar winds from massive stars and supernova explosions from the massive-star formation.

- Not all edge-on spirals reveal linear dust lanes. A Hubble image of another galaxy called ESO 510-G13 reveals a warped disk. This galaxy is at a distance of about 150 million light-years, and it's roughly the same size as the Milky Way, but its disk is warped. These kinds of warps suggest recent interactions with another galaxy. It may have actually generated a starburst as well, because there is a bluish region in the right part of the disk of this galaxy that may be related to a starburst associated with that closer pass of another galaxy.

- NGC 6670 is a pair of edge-on spirals that are actually in the process of colliding. It is about 400 million light-years away. In an image of NGC 6670, the nuclei of the two galaxies are about 50,000 light-years apart. Amidst the dust, you see the bright blues, which indicate a starburst. The infrared luminosity due to heated dust in this colliding pair is equal to 100 billion Suns.

- The most famous starburst galaxy is located only 12 million light-years away. The Hubble image of this galaxy, known as M82 or the Cigar Galaxy, looks like its middle has exploded. You see reddish plumes of nebular gas and dust rising 10,000 light-years from the core. But when you look away from what's going on at the core, its bluish main body looks like an inclined spiral.

- Hubble can peer inside the core of M82, and a core close-up reveals about 200 fuzzy bright spots, each of which is a cluster of stars about 20 light-years across with up to a million young, massive stars. The innermost 1000 light-years of this galaxy have 10 times the star birth rate of the entire Milky Way Galaxy.

- When so many massive stars are formed at the same time, this massive starburst generates what's called a galactic super-wind. All of the strong stellar winds and the supernova explosions associated with these massive stars are blowing out tremendous amounts of gas. At the same time, it's compressing gas in other places and making more stars. This kind of tremendous starburst activity not only leads to forming more stars, but it also blows a lot of gas out of the inside of the galaxy.

- You see this not only at high resolution with Hubble, but when you take images of M82 with the Chandra X-ray Observatory and the Spitzer infrared observatory, you see the same kind of starburst effects associated with the starburst in these outflows. You see bright X-ray sources near the core and diffuse hot gas rising from it. In the infrared, Spitzer reveals even larger plumes of heated dust coming out of the center of M82. Indeed, this galaxy is the brightest infrared galaxy in the entire sky.

- Why is M82 undergoing such a massive starburst? A wide-field optical view shows a large spiral galaxy called M81 that's about 130,000 light-years away from M82. Based on the motion measured of these galaxies, it appears that M81 passed very close to M82 a few hundred million years ago. What could have happened as M81 came close to M82 is that the tidal force associated with its gravity could have compressed the core gas clouds on M82 and begun this massive starburst. Even close "misses" between galaxies can have significant impacts on their appearance and evolution.

Hoag's Object

- Our feature galaxy in the Hubble zoo was discovered by the American astronomer Arthur Hoag in 1950. Given its beautiful symmetry, it would seem to be a far less likely product of an interaction with another galaxy than the cosmic violence associated with M82. Hoag's Object is about 10,000 times fainter than the naked-eye limit, and it's only about 45 arc seconds across. Its yellow core of old stars is about 17,000 light-years across, and the blue ring of young stars has inner and outer diameters of 75,000 and 120,000 light-years. The galaxy space between the core and the ring appears almost essentially empty.

- Hoag's Object is classified as a ring galaxy. The Cartwheel Galaxy is also a member of this rare class. The idea of ring galaxies and how they're produced can be explored further with snapshots in time of other ring galaxies. Arp 148 is an interacting pair of galaxies about 500 million light-years away. Ring evolution is farther along in another galaxy called AM 0644-741, which is about 300 million light-years away. Arp 147, which is 400 million light-years away, is another case that is well past a collision.

- In all of these other ring cases, the likely collision partner that stimulated the formation of the ring was nearby. Such is not the case for Hoag's Object. There is no other galaxy anywhere near it. Some non-collision ideas have been put forward, but all of them have trouble explaining the simple symmetry of the ring structure in Hoag's Object.

Suggested Reading

Mackie, *The Multiwavelength Atlas of Galaxies*.

Sparke and Gallagher, *Galaxies in the Universe*.

Struck, *Galaxy Collisions*.

Questions to Consider

1. Describe the night sky as viewed from a planet around a star on the inner edge of the blue ring of stars in Hoag's Object.

2. How could one distinguish two similar elliptical galaxies in the same line of sight at distances of 100 million and 120 million light-years?

The Brightest Quasar

Lecture 15

The supergiant elliptical galaxy M87 is larger and much more massive than the Milky Way, with a 6-billion-solar-mass black hole at its center. M87 has grown over time through collisions with other galaxies in the Virgo cluster. Such collisions can trigger the infall of gas onto the black hole, leading to the observed jet of material being ejected from its core. About 10 degrees on the sky away from M87 lies the first quasar to be identified, known as 3C 273. It is also the brightest one on the sky. Viewed up close with Hubble, 3C 273 reveals a 100,000 light-year-long jet consistent with its power source being a supermassive black hole.

Exploring the Sky with New Technology

- The biggest discoveries in astronomy often originate from observing the sky at previously unexplored wavelengths with new technology. As radio astronomy began to blossom in the 1950s, astronomers detected a number of bright radio sources on the sky and began to catalogue their positions. One of the most famous such catalogues was compiled by scientists at Cambridge University in England and is known as the third Cambridge, or 3C, catalogue.

- These radio sources that were discovered couldn't be due to normal stars, because stars are typically radio-faint. If you have unusual sources emitting radio light, you really want to observe them at other wavelengths—in particular, optical observations. But this was very difficult at the time because the positions of these radio sources on the sky were poorly known.

- The reason these positions were poorly known is because of the limitations of imaging the sky in terms of resolution with single-dish radio telescopes. For example, the Parkes radio telescope in Australia has a dish that is 64 meters in diameter. With this dish at radio wavelengths—specifically, at 20 centimeters—Parkes resolves the sky at a resolution of 11 arc minutes, which is too low to fix on

any particular optical source. But as the Moon passes in front of that object, you can use the occultation to fix the radio position.

- In 1962, astronomers realized that the 273rd object in the 3C catalog would be occulted by the Moon. The Moon would be passing over that part of the sky. At that time, the Parkes radio telescope was used to observe 3C 273, and the position of this radio source corresponded to, at optical wavelengths, a blue starlike object. This object was bright enough to be seen with a small telescope.

- Eventually, a few other radio sources were pinpointed like 3C 273 was. Interestingly, they also matched up with what looked to be bluish-looking stars. These objects became known as quasi-stellar radio sources, which was shortened to the word "quasar." The nature of these quasars was a complete mystery, even though they'd been identified at optical wavelengths, because stars simply shouldn't be radio-bright.

- Among the astronomers puzzling over the nature of quasars during the early 1960s was Maarten Schmidt, a young astronomy professor at CalTech, which had access to the world's largest telescope: the Palomar 200-inch. This telescope had its first light in 1948, and it was the largest ground-based optical telescope on the planet for 45 years.

- With the Palomar, Schmidt obtained a spectrum of 3C 273, which looked nothing like a galactic star. Typically, galactic stars exhibit narrow absorption lines in their spectrum, but this object exhibited broad emission lines. At first, he couldn't match the emission lines he found with any known element. He then realized that these were actually hydrogen emission lines, and they had been redshifted by a tremendous amount. The redshift velocity measured was 48,000 kilometers per second.

- This object, 3C 273, was flying away from the Milky Way at one-sixth the speed of light. In terms of Hubble's law, this implied that 3C 273 was 2 billion light-years away. In 1963, Schmidt

published a paper that quasars were likely extragalactic—a breakthrough discovery.

- An extragalactic origin for 3C 273 led to even more astonishing implications. With a redshift distance of 2 billion light-years, the quasar's brightness requires an intrinsic optical luminosity equivalent to 100 Milky Way Galaxies.

- How could a starlike object be that luminous? First, we need to estimate its physical size. This can be done by monitoring its brightness. 3C 273 can vary by about 0.6 magnitude, or 2 times over a month. The timescale of variation gives us an indication of how big the light-emitting region is of the object that's varying.

- Imagine an object with a radius of a light-month. Imagine that it brightens throughout in an instant. A distant observer would see variation over a month. This implies that the light-month-sized 3C 273 can emit 100 Milky Ways' worth of light. It is too tiny to power 100 Milky Ways. A supermassive black hole would be the only thing that could be small enough and powerful enough to power such a thing.

- Such a black hole would require infall of a few solar masses per year on a black hole that measures about a billion solar masses. Such a supermassive black hole would have an event horizon radius of 20 astronomical units. The matter falling onto this black hole would form a large accretion disk around the black hole. The disk itself could be light-days to perhaps light-weeks in radius.

- As the matter falls into this disk, the gravitational energy of the infalling matter heats up the disk. Through this gravitational energy, the black hole unlocks about 10 percent of the infall mass and converts it to energy. The radiation of this disk energy matches quasar luminosity. The radiation from the disk also causes any surrounding gas clouds in the vicinity to glow, and that's what produces the emission lines seen in optical spectra of 3C 273.

- The radio emission produced by 3C 273 would be produced by the fast electrons in the hot gas associated with this system. Due to the magnetic fields associated with this accretion disk, jets of high-speed particles can be emitted from this object. Mass infall rate fluctuations may lead to quasar variability.

Quasars

- Since Schmidt's discovery paper on 3C 273, the idea that quasars are powered by supermassive black holes at the cores of distant galaxies has found wide support from a variety of ground- and space-based observations. In particular, high-resolution optical images of 3C 273 taken with two different cameras onboard the Hubble Space Telescope have revealed structure in its associated jet and the faint host galaxy of the quasar.

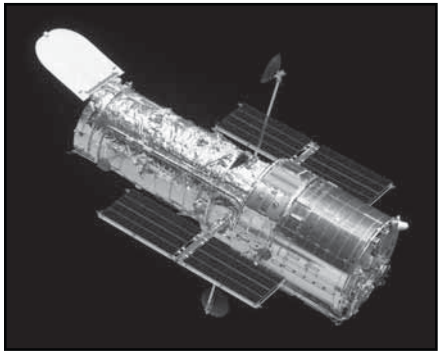
- Even at Hubble's fantastic resolution, 3C 273 looks like a star. The only unusual hint is a clumpy line of light pointing to it—a jet. The jet of 3C 273 is the brightest optical quasar jet ever found. It was noted in 1963 by Maarten Schmidt. It begins at an angular distance of about 12 arc seconds from the quasar, and it's about 10 arc seconds long. At the distance of 3C 273, this length corresponds to about 100,000 light-years. In other words, this jet has the same width as the Milky Way Galaxy.

- The jet is not only observed at optical wavelengths; it's also seen in the radio from the ground and at infrared and X-ray wavelengths. Chandra observations show that the closer clumps in this jet are brightest in X-rays. The clumps that are farther away from 3C 273 are brighter in radio and at infrared wavelengths as observed by Spitzer.

- The jet is caused by hard-charged particles like electrons and protons moving at extremely high speed—almost at the speed of light. As these particles are fired out from the supermassive black hole, they spiral along the magnetic field lines associated with these jets.

- The whole idea behind this model begins with this rotating accretion disk and the magnetic field associated with it. And this twisted field

focuses and accelerates these polar jet outflows, or these charged particles, to very high velocity. The exact jet mechanism is not yet completely understood. However, only a supermassive black hole has the power to drive such a large, energetic jet.



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The incredible discoveries of the Hubble Space Telescope have revolutionized the field of astronomy.

- Because a supermassive black hole needs to eat a steady and healthy supply of matter to maintain the energy output of a quasar, one would typically expect quasars to be associated with gas-rich galaxies. Hubble observations of the faint nebulosity around 3C 273 and other quasars have been vital in clearly establishing this link.

- Hubble shows a 30-arc-second close-up on 3C 273 as observed with its advanced camera. The occulting disk on the camera eclipses the bright quasar point source, revealing a faint underlying spiral galaxy that's over 60,000 light-years across.

- Hubble has imaged many other host galaxies to quasars, including ones ranging from 1.5 to 3 billion light-years away. Some of the quasars are at cores of seemingly normal spirals, and some are at the cores of seemingly normal elliptical galaxies. But many are associated with interacting galaxies—galaxies colliding with one another.

- Hubble also has imaged the aftermath of a collision between two galaxies hitting each other at a speed of 500 kilometers per second. The topmost point source is actually a foreground galactic

star, but below the quasar, we see evidence of the starburst in this spiral remnant.

- The Hubble images show us that quasars can be found in a variety of galaxies. Interacting cases are understandable. If there is a supermassive black hole in the mix, if you have two galaxies colliding, a lot of gas can be dumped on that supermassive black hole, which stimulates quasar activity. But how can so-called normal ellipticals and normal spirals house quasars? Note that the supermassive black hole is just a tiny fraction of the galaxy size and mass. The key challenge is figuring out how they deliver mass to the quasar.

- A key to better understanding the connection between quasars and galaxies is the distribution of quasars on the sky as a function of distance. Surveys have mapped over 200,000 quasars and have found that there are very few of them nearby. 3C 273 is actually among the closest 1 percent. Quasars peak in number at a distance of 10 billion light-years. This means that quasars were much more common long ago. The idea behind this evolution is that the quasars faded as their supermassive black holes ran out of gas. If this idea is true, one would expect to find many supermassive black holes still around at the centers of galaxies we see nearby.

- M87 is the largest elliptical galaxy in the Virgo cluster. It's a strong radio emitter, and it has a conspicuous jet. In studying this jet over time, Hubble has seen flares in the jet. Indeed, a flare called HST-1 was found to be only 200 light-years from the core of the galaxy. What is this flare due to? Perhaps there was a flare in the magnetic field associated with the jet, or perhaps a gas cloud inadvertently wandered in front of the jet and the jet hit an intervening gas cloud and lit it up.

- The deep Hubble image of the core of M87 also indicates that its supermassive black hole is just a bit off-center. Perhaps this is due to a semi-recent collision with another galaxy, maybe even a merger with another supermassive black hole.

- When we look at M87 with radio wavelengths, we see that the jet emission that we see at optical extends out many thousands of light-years. If we look at radio wavelengths very close to the center, we see that there is radio emission within 0.1 of a light-year at the core of M87. These observations are indicative of a semi-retired 6-billion-solar-mass black hole. Perhaps long ago, with more infall and steadier infall, it was a quasar.

- Overall, the observations clearly indicate that supermassive black holes are commonly found at the centers of large galaxies in the local universe. The level of activity associated with these supermassive black holes varies and is typically a function of recent interactions with other galaxies leading to an episode of mass infall. There are two other nearby cases: Alpha Centauri and M31, our nearest neighbor.

Suggested Reading

Bartusiak, *Archives of the Universe*.

Kitchin, *Galaxies in Turmoil*.

Scharf, *Gravity's Engines*.

Questions to Consider

1. Describe the night sky as viewed from a planet around a star in the outskirts of the spiral host galaxy of 3C 273.

2. How might one interpret a quasar with no optically observable host galaxy?

The Dark Side of the Bullet Cluster

Lecture 16

The existence of dark matter is key to our understanding of a wide range of phenomena in the universe, ranging from its large-scale structure to the collisions of galaxy clusters. Through space observations of gravitational lensing and hot gas with Hubble and Chandra, the image of the Bullet cluster provides one of our best visualizations of dark matter. However, the answer to the fundamental question regarding the composition of this dark stuff remains elusive.

Dark Matter

- Dark matter is basically defined as matter that interacts with visible matter through gravity but not through electromagnetic radiation. Consequently, it can be detected through its gravitational effects on visible matter and radiation, but it does not emit or absorb photons.

- Where is this dark matter? Let's start with our neighborhood. Is there gravitational evidence for a large amount of dark matter in the Milky Way?

- The Sun has more mass than everything else in the solar system combined. The outer planets orbit much slower than the inner planets. This is exactly what one would expect gravity to do if, indeed, the Sun has most of the mass in the solar system. In other words, there's no need for any dark matter in the solar system to explain the gravitational interactions of the planets.

- The orbital velocities of the stars around the center of the Milky Way reflect their mass interior to them, between them and the galactic center. The mass inside a particular star's orbit around the galactic center is proportional to the rotational velocity of that star squared, times the distance of that star to the galactic center. The amount of mass interior to the Sun's orbit around the galactic center is about 100 billion solar masses.

- If light in the Galaxy traces mass—the light is decreasing as we go to the outer part of the Galaxy—the velocities of these stars should decrease and end up with velocities less than what we see at the Sun's velocity around the galactic center. Indeed, we can measure the velocities well past the Sun's orbit to sparse regions, and we find that the velocities don't decline as expected. In other words, light doesn't trace mass. Therefore, we say that the Galaxy exhibits a flat rotation curve, which indicates that there must be a substantial amount of dark matter in the Milky Way.

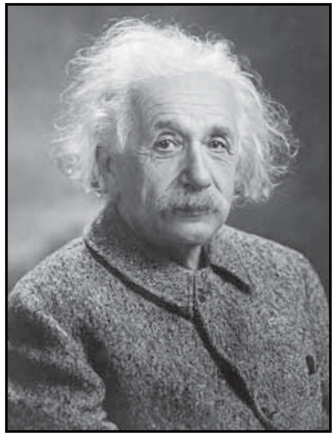
- This is best understood in terms of a vast halo of dark matter. The amount of mass in this dark matter halo is appreciably greater than the amount of mass in the visible disk. The dark matter that we expect is filling the broad halo around the disk of our Galaxy is most likely some kind of non-baryonic particle. Protons and neutrons are particles we call baryons.

- Almost every spiral galaxy in the universe that we study exhibits these flat rotation curves. In other words, we can observe the rotational velocities out as far as we can see the stars, and they don't drop off, whereas they should if the only amount of matter in these galaxies were the matter tied to the stuff that's shining. These observations tell us that there is indeed a significant amount of dark matter associated with individual galaxies.

- Distant rich clusters of galaxies provide an opportunity to explore the presence of dark matter on a larger scale. Abell 1689 is one of the most massive clusters known. It is located at a distance of 2.2 billion light-years. A high-resolution Hubble image of the cluster spans 2 million light-years and reveals its high density of many hundreds of galaxies.

- It also reveals hundreds of thin, arc-like structures. Indeed, many of them appear to partially encircle the cluster core. If we look at them close up, we see a variety of cases. We see some arcs that are short and some that are long. We also see multicolor arcs.

- Amazingly, Hubble is able to see these arcs and these rich clusters because of its sharp eye. In the case of Abell 1689, these arcs are due to galaxies that are far beyond this galaxy cluster. As they go through the cluster's gravitational field, these images of very distant galaxies are amplified and distorted. In other words, Abell 1689 is a gravitational lens. Such a lens is due to the space curvature around massive objects.



Albert Einstein (1879–1955) predicted space curvature in his general theory of relativity.

- This kind of space curvature was predicted by Einstein's general theory of relativity in 1916. In this theory, gravity is effectively a manifestation of this space curvature. The idea is that when you have massive objects in space, they curve the space around them such that less-massive objects follow that space. If they travel through space, they follow the curvature of space when they pass through a massive object. Light must also follow this curvature of space.

- A good example of this is the case of our solar system. The Sun itself curves the space around it, and the planets orbit in this curved space surrounding the Sun's mass. Starlight passing right near the edge of the Sun is bent by an angle of 1.7 arc seconds due to the space curvature associated with the mass of the Sun. Evidence of this was seen during a solar eclipse in 1919. This was a key confirmation of Einstein's general relativity.

- The extent to which the space curvature around a massive cluster of galaxies makes it a gravitational lens depends on a number of factors, including its mass distribution, size, and distance, plus its alignment with the background galaxies and the distances of those galaxies.

- A background galaxy can be lensed into multiple images. Lensing produces arc-like images bent from "true" positions. Through this lensing, you can brighten some of these galaxies, making them brighter than they would appear if you didn't have this kind of lens.

- The lensed images can change over time due to the changing mass distribution in an intervening cluster of galaxies. The structure of the arcs is sensitive to this complex cluster mass distribution. If you can measure actively the positions and shapes of these lensed images, you can get a map of the lensing mass of the intervening cluster of galaxies.

- The many lensed images we see in the case of Abell 1689 makes this particular case ideal for working out the mass distribution of the total mass in this cluster. The lensing yields the total mass distribution—both the mass that's dark and the mass that's shining at different wavelengths. It does not differentiate between visible and dark matter.

- The lensing gives you the total amount of mass, and then you assess the dark contribution by subtracting the matter you see—by estimating how much mass is associated with the stuff that's shining. In this case, the subtracted visible part for the map has two components. First, the optical galaxy light gives us a mass estimate of the stars in Abell 1689. (The dark matter appears to correlate quite well with the visible galaxy density.) Second, the X-ray image of the cluster gives us a mass estimate of the hot gas between the galaxies in Abell 1689.

- Intracluster hot gas is common in rich clusters. Overall, individual cluster studies show that dark matter is dominant in these clusters. Specifically, dark matter is about 5 times more abundant than visible matter. In addition, the dark matter is distributed more smoothly, like the intercluster hot gas, than galaxies.

The Bullet Cluster

- Observing the collision aftermath of two galaxy clusters provides an opportunity to test this composition and our understanding of dark matter. In such a collision, the colliding clouds of hot gas should slow due to ram pressure, while the dominant dark matter should not if it only interacts with itself and the gas through gravity.

- The textbook case of a galaxy cluster collision is located at a distance of 3.4 billion light-years. At optical wavelengths, the Bullet cluster appears as a large group of galaxies separated by about 2 million light-years from a smaller group. The Hubble optical image alone doesn't indicate a collision; the Chandra X-ray image is the key.

- An optical/X-ray image shows that the collision separated the galaxies and the hot gas. But what about the dark matter? With Hubble's fantastic detail, we can study the lensing effects and understand the total amount of mass associated with this cluster. The derived lensing mass, which is dominated by dark matter, is clearly separated from the hot gas. This observation is completely consistent with the idea that the cluster is dominated by dark matter.

- Since the original study of the Bullet cluster, several other colliding galaxy clusters have been observed in detail with Chandra and Hubble. For example, the Musket Ball cluster is at a distance of 5.2 billion light-years, and the rich cluster Cl 0024+17 is at a distance of 5 billion light-years.

- The rich cluster Abell 520 is at a distance of 2.4 billion light-years. Comparing Hubble's image with Chandra's X-ray image and information about total mass from the lensing studies, we see that the hot gas is in the middle and is consistent with a collision between two clusters. The optical luminosity is the light associated with the galaxies in these clusters and is consistent with the cluster separating. But the lensing mass that is dominated by the dark matter is mostly in the middle.

- Why didn't the dark matter separate with the galaxies? This is a puzzle. But there are several possibilities to explain this complex composite, which looks like a train wreck. The most revolutionary possibility would be that some dark matter is a bit sticky. When the clusters collided, their dark matter interacted like the hot gas. However, other cluster collision cases show non-sticky dark matter behavior.

- Alternatively, perhaps Abell 520 is a collision of three clusters, or perhaps the core dark matter clump involves matter far from Abell 520. The bottom line is that Abell 520 is a puzzle for further observations to answer.

- It is possible to use weak gravitational lensing to map the distribution of dark matter on scales much larger than that of clusters of galaxies. Such studies utilize high-resolution optical images to accurately measure the shapes of distant galaxies and statistically look for subtle distortions due to the space curvature provided by foreground concentrations of mass.

- A number of observatories both from space and the ground have worked together to produce something called the COSMOS survey. The Hubble Space Telescope covered 2 square degrees of the sky, and for Hubble, that's a lot of space to cover. Indeed, the COSMOS Hubble image is a mosaic of 575 individual pointings with Hubble and a total of 1000 hours of observation, which is a tremendous amount of time to put into a Hubble observation. This Hubble map shows that the visible matter appears to accumulate where the dark matter is densest.

- Measured galaxy distances provide a three-dimensional perspective of how the dark matter changes with distance and with time deep into the universe in one particular place in the sky. A three-dimensional map shows a network of dark matter filaments. Because of gravity, dark matter filaments get clumpier as the universe ages. The idea is that dominant dark matter filaments formed early in the history of

the universe. Then, visible matter is drawn by dark matter gravity to these filaments, and visible galaxies and clusters evolve along them.

- Models predict a present-day cosmic web of dark matter filaments. A simulation of this web that is a little over 1 billion light-years across predicts that there should be filaments of clusters of galaxies across the sky and voids tens of millions of light-years across. In fact, this prediction of this web of structure in the universe is matched pretty well by the observed large-scale distribution of galaxies.

Suggested Reading

Gates, *Einstein's Telescope*.

Panek, *The 4 Percent Universe*.

Weaver, *The Violent Universe*.

Questions to Consider

1. Why are space observations vital to the study of dark matter?

2. If dark matter is the dominant form of matter in the universe, why don't we see any evidence of it on Earth?

The Cosmic Reach of Gamma-Ray Bursts

Lecture 17

It is amazing to think of all the discoveries of gamma-ray bursts that have followed from the serendipitous space discovery of a few brief gamma-ray flashes over 40 years ago. Without the view from space of these initial clues, we might still be missing the most powerful explosions in the universe and some of the deepest views into the cosmic past. The rich history and science of gamma-ray bursts are reminders that it is important to explore the entire electromagnetic spectrum for new cosmic phenomena, especially in the case of the transient sky.

Gamma-Ray Bursts

- The brightnesses of many stars vary on timescales ranging from hours to years. Most of these variations are either too slow or too small to be easily discernable to the naked eye. The rarest cases involve a huge increase in brightness on a very short timescale, where it looks like a new star has suddenly appeared. Such optical transients are typically associated with an explosive event, such as a supernova.

- The most perplexing transients were first detected through space observations of the gamma-ray sky in the late 1960s. These gamma-ray bursts lasted only a few seconds, left no detectable traces at other wavelengths, and were difficult to fix on the sky. Consequently, their origin was completely unknown.

- The discovery of astronomical gamma-ray bursts was completely serendipitous. Amazingly, it came about as a result of the treaty signed by the Soviet Union, Great Britain, and the United States in 1963 to ban tests of nuclear weapons anywhere above ground, including outer space and underwater.

- In order to ensure treaty compliance, the United States launched the Vela series of satellites in the 1960s to monitor the Earth and

its environment for the gamma-ray signature of any nuclear explosions. The Velas never detected any nuke signatures, multiple Velas did detect brief gamma-ray bursts.

- However, it was very difficult to locate the source. Energetic gamma rays are very difficult to focus. Multiple Vela satellites could give you a rough triangulation by the arrival time of the pulse, and this triangulation showed that the source was not a solar system object. Over the subsequent 3 years, the Vela satellites detected 16 such bursts. In 1973, a discovery paper was published, heralding this new cosmic phenomenon.

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Gamma-ray bursts collect a massive amount of energy into narrow beams.

- The keys to understanding the gamma-ray bursts were to identify the sources on the sky at other wavelengths, measure their distances, and determine their true energies. As the 1970s turned into the 1980s, the observational effort thus focused on better localizing the sky locations of the gamma-ray flashes.

- Other spacecraft far from Earth with gamma-ray detectors were utilized to get much better triangulation and focus of where on the sky these gamma-ray bursts were. Among the hundreds of new gamma-ray bursts that were discovered during this interval, dozens were actually located to a few arc minutes. But a few arc minutes is still a big hunk of sky, and there are many thousands of stars and galaxies in such a small space. Through the late 1980s, no one found any counterparts to the gamma-ray bursts at any other wavelengths.

- By the time NASA launched the Compton Gamma Ray Observatory in 1991, almost 20 years had passed since the discovery of gamma-

ray bursts, and there was still no convincing evidence of their origin. The Burst and Transient Source Experiment (BATSE) onboard Compton was designed to be 10 times more sensitive to gamma-ray bursts than all previous missions.

- BATSE had eight detectors on the corners of the spacecraft, and with these different detectors, it could isolate a gamma-ray burst on the sky to a window of 10 degrees. This is too large to identify a counterpart to a specific gamma-ray burst.

- However, the greater sensitivity of BATSE on board Compton led it to actually discover one gamma-ray burst every day. In other words, if you build up a large number of statistics of where they occurred on the sky, you can look at all of those sky locations and deduce what might be going on. Specifically, if the source of these gamma-ray bursts were in the galaxy, we would expect that they would be concentrated on the Milky Way, because that's where most of the stars in the Milky Way are.

- Over the course of its 9-year life, over 2700 gamma-ray bursts were detected with BATSE. And it discovered that their sky distribution was completely isotropic. They were found all over the sky. This finding was most consistent with an extragalactic interpretation. If these gamma-ray bursts were occurring far beyond the Milky Way, that would imply that they have huge energies.

- BATSE also was able to establish that there were two different gamma-ray burst populations. Most of them are long-duration bursts, which tend to last more than 2 seconds, but there are also smaller populations of bursts that have a somewhat shorter duration.

- In order to confirm an extragalactic origin, it would be necessary to nail down a gamma-ray burst source. This feat was first accomplished by the Italian-Dutch X-ray satellite observatory BeppoSAX with a gamma-ray burst on February 28, 1997. It caught the fading X-ray afterglow of the gamma-ray burst and isolated its position within 1 arc minute.

- This position was quickly advertised, and a ground-based image was taken 20 hours after the gamma-ray burst. The fading optical dot fixed the position within 1 arc second. A later Hubble image found a faint galaxy around this spot. Its redshift indicates a distance of 5 billion light-years.

- Several other BeppoSAX gamma-ray bursts were soon tied to distant galaxies. Their implied burst energetics were enormous. Given the brightnesses and huge distances, these gamma-ray bursts were the most powerful explosions since the big bang. Their peak power was millions of times more powerful than that of a supernova.

- What could explain an explosion that appears much more powerful than a supernova? The leading possibility for the long-duration bursts is a supernova where much of the energy is tightly beamed into opposing jets—one of which is pointed at the observer. Such a supernova can arise when the core of a very massive star collapses into a rapidly rotating black hole and an accretion disk.

- There is a reasonable amount of initial supporting evidence for this so-called hypernova model. First, the host galaxies of these gamma-ray bursts typically appeared to be star-forming galaxies with many massive stars in them. Second, several of the nearest gamma-ray bursts had bright supernovas accompanying the gamma-ray burst. Third, gamma-ray bursts basically take all the energy that you could imagine coming out isotropically in a typical supernova and collect it into narrow beams of energy. This beamed model implies that there are many more gamma-ray bursts than we can see.

The Swift Space Observatory

- In order to test the hypernova model and explore other gamma-ray burst possibilities, it would be necessary to systematically study a large number of gamma-ray bursts, their afterglows, and their host galaxies. The Swift space observatory launched by NASA in 2004 was designed to respond to gamma-ray bursts faster than any mission that had come before it.

- Swift and its three instruments can detect and localize a gamma-ray burst within seconds to a few arc minutes in position and then pivot the spacecraft so that it can image the gamma-ray burst at X-ray, ultraviolet, and optical wavelengths to arc-second precision within a few minutes. Gamma-ray burst position is then quickly advertised for ground follow-up. By 2010, Swift had detected 500 gamma-ray burst, and it found that over 90 percent of them had X-ray afterglows, and over 50 percent had optical afterglows. Through this kind of information, distances have now been determined for well over 100 of these gamma-ray bursts.

- Perhaps the most remarkable gamma-ray burst observed by Swift occurred on March 19, 2008. Its long gamma-ray pulse lasted about 60 seconds, with an energy among the highest ever measured for a gamma-ray burst. Its X-ray and optical afterglow initially blinded the Swift detectors. Indeed, the optical afterglow was by far the brightest ever recorded for a gamma-ray burst.

- It was easily seen by ground-based all-sky monitors. It was bright enough to be seen with the naked eye for 30 seconds. It then quickly faded by 100 times in about 3 minutes. Its redshift indicates a distance of 7.5 billion light-years. This is the most distant thing ever detectable by eye by far. It easily beats M33 at 2.8 million light-years, and it's even farther than 3C 273 and the Bullet cluster.

- Why was this gamma-ray burst so luminous? Indeed, it was 2.5 million times more luminous than a typical supernova. It's possible for such a gamma-ray burst to be that bright in the context of the hypernova model, but it would require an extremely narrow jet. In other words, we just were lucky enough to be within that jet, which must have been on the order of 0.4 degrees wide. And the jet ejecta had to be moving at a speed on the order of 99.99995 percent the speed of light. That is a rare view inside the beam of such a narrow jet.

- What if a gamma-ray burst like this one occurred in the Milky Way? The very massive star Eta Carinae will likely explode as a

supernova sometime in the next several 100,000 years. Suppose that it explodes as a gamma-ray burst just like the one on March 19, 2008, with a jet pointed right at Earth. Given Eta Carinae's distance of 7500 light-years, such a gamma-ray burst would be almost as bright as the Sun on the sky.

- The optical flash from Eta Carinae as a gamma-ray burst wouldn't hurt the Earth, but the gamma rays themselves, even though they might not last for a long time, would have a dramatic effect on the atmosphere.

- The gamma rays would destroy much of the ozone layer on the facing hemisphere of Earth. Globally, the ozone layer would be reduced by more than 30 percent. The solar ultraviolet increase would kill many microorganisms. This effect could ripple up the food chain, resulting in a possible mass extinction. It would take years for the atmosphere to recover. Other radiation effects could also help promote an extinction.

- Should we add gamma-ray bursts to our cosmic worry list? There is no definitive evidence of past gamma-ray-burst-caused mass extinctions. In addition, Eta Carinae's rotation axis is not pointed at Earth. And long gamma-ray bursts are rare in mature spirals like the Milky Way. Their galaxy hosts are mostly distant star-forming dwarf irregulars. These young galaxies have low metals and many massive stars. NGC 4214, which is 5000 light-years across, is a nearby example, at a distance of 10,000,000 light-years.

- Such young galaxies were much more common when the universe was younger. Thus, it is not surprising that most of the long gamma-ray bursts correspond to distances greater than 7 billion light-years. The Hubble Ultra Deep Field is the deepest optical image of the universe made to date. Among the 10,000 galaxies in this image spanning a few arc minutes, the most distant are small, active star-formers dating back to less than a billion years after the big bang.

Suggested Reading

Bloom, *What Are Gamma-Ray Bursts?*

Mazure and Basa, *Exploding Superstars*.

Wheeler, *Cosmic Catastrophes*.

Questions to Consider

1. Why has the origin of gamma-ray bursts been so difficult to pin down? Would it have been easier if they were similarly brief, non-repeating radio bursts?

2. According to the hypernova model, why is it extremely unlikely that any gamma-ray burst in the local universe would originate in an elliptical galaxy?

The Afterglow of the Big Bang

Lecture 18

As the ultimate background, the cosmic microwave background frames all of the foreground dust, stars, and galaxies that you have learned about throughout this course. The cosmic microwave background also provides a background in time as the afterglow of the big bang. The signature of its anisotropies reflects the evolving cosmos through which we observe this most ancient light. In this course, as you have traveled from the Earth through the solar system and the Milky Way to the most distant galaxies, quasars, and gamma-ray bursts, you have learned how vital space probes and space observatories have been to our understanding of the cosmos.

The Big Bang

- As we gaze out farther into space with Hubble, we see galaxies at distances of millions to billions of light-years in images that span over 10 billion years in time. At optical wavelengths, all of these galaxies are framed in a background of darkness. Does this ultimate background extend back to a particular time, or is it infinite in its depth?

- The key clue to its understanding comes from much longer wavelengths, where the sky is bathed in a background of microwave radiation. The simplest interpretation of this radiation is that it dates back to a time 13.7 billion years ago, when the universe was much smaller, hotter, denser, and as bright as the Sun.

- Detailed observations of the cosmic microwave background with the Wilkinson Microwave Anisotropy Probe space observatory have revealed tiny variations indicative of density fluctuations in the early universe. As the universe expanded and cooled, these fluctuations evolved into the large-scale structure of galaxies seen today.

- The view that the cosmos is evolving from a singular origin in time is consistent with observations of quasars as a function of distance

and Edwin Hubble's discovery that the universe is expanding. However, prior to 1965, there was no smoking gun pointing conclusively to a hot big-bang model.

- The idea of such a big bang was first explored quantitatively by the physicist George Gamow and his students Ralph Alpher and Robert Herman shortly after World War II. They really weren't focused on what caused the big bang itself; instead, they were thinking about what would have happened shortly after the big bang. At those times, such a universe would be very hot and very dense and have characteristics very similar to what we find at the centers of stars today: nuclear fusion, or the conversion of hydrogen into helium and heavier elements.

- In 1949, Alpher and Herman published a paper that looked at the radiation that would be associated with a big-bang universe. At these early times, they realized that there would be a lot of radiation, and the radiation would acquire a blackbody spectrum. At those early times, this would be a very hot blackbody spectrum. It would peak at X-ray to gamma-ray wavelengths. As the universe expanded and cooled off, this blackbody radiation would also slowly cool off.

- In thinking about this, Alpher and Herman realized that this radiation signature could still be observed today. They predicted that even today there should be existing afterglow of the big bang observable as an approximately 5-degree-kelvin blackbody that would peak at microwave wavelengths. At the time, they also realized that the technology didn't exist to try to detect such a faint signal peaking at microwave wavelengths.

- By the 1950s, it became clear that the big-bang fusion of the elements didn't work beyond helium and lithium. The reason is, simply, that the universe expanded too fast. During this same time, other scientists discovered that the bulk of the elements in the periodic table are produced through stellar nucleosynthesis, not big-bang nucleosynthesis. As a result of this evolution in thinking,

the work that Alpher and Herman did on the cosmic microwave background was essentially forgotten.

- In 1965, at Bell Labs in New Jersey, Arno Penzias and Robert Wilson were testing sensitive microwave-receiving systems for satellite communications. They were doing this work with a 20-foot horn antenna, working at a radio wavelength of about 7 centimeters.

- In doing this work, they found that there was always a source of noise in their measurements. This noise was equivalent to something with a radiation temperature of about 3.5 degrees kelvin. It was completely isotropic across the sky, and there were no variations with time. They checked their antenna to see if there was some kind of problem with it or if there was some source of noise in the neighborhood. They found no terrestrial explanation. They were also completely unaware of the prediction that Alpher and Herman had made about 16 years earlier.

- Eventually, they made contact with a group of Princeton astrophysicists who had independently repredicted Alpher and Herman's original calculations. Together they realized that Penzias and Wilson had discovered the afterglow signature of the big bang itself—this cosmic microwave background. In 1978, Penzias and Wilson won the Nobel Prize for this completely serendipitous discovery.

- Perhaps the most amazing twist to this story is that indirect evidence of the cosmic microwave background actually first arose in 1941. This evidence involved the nearby runaway star Zeta Ophiuchi. The Spitzer infrared images of Zeta Ophiuchi had a beautiful infrared bow shock. Any optical light that might be associated with this bow shock would be obscured by the dust cloud in front of Zeta Ophiuchi, making it so much fainter than it would be without the dust in front of it. In addition to the dust in this cloud, the cloud also contains simple molecules, including cyanogen molecules. This molecule can be found in an optical spectrum of Zeta Ophiuchi.

- In 1941, Canadian astronomer Andrew McKellar set out to analyze this weak cyanogen absorption. He found that the cyanogen molecules were being heated up by something. This seemed to indicate that space had a temperature of about 2 degrees kelvin. He published this result in an optical astronomy journal. If Gamow, Alpher, and Herman had read McKellar's paper in 1949, they could have seen that the microwave background they predicted had been discovered.

- After Penzias and Wilson, it was realized that the cyanogen was sampling this cosmic microwave background radiation at a wavelength near the wavelength peak of the radiation—a wavelength where we can't directly see it because of our atmosphere's obscuration.

The Cosmic Background Explorer

- In order to better measure the predicted blackbody spectrum and isotropy of the cosmic microwave background beyond the obscuration of our atmosphere, space observations of increasing sensitivity have been carried out over the past 25 years.

- The Cosmic Background Explorer (COBE) was launched in 1989 to pioneer this space effort. It was equipped with three instruments—DIRBE, DMR, and FIRAS—and cooled by liquid helium and a thermal shield to block any contaminating radiation from the Earth and the Sun. FIRAS yielded the first really important result from COBE. It found that this radiation had essentially a perfect blackbody spectrum with a temperature of 2.73 degrees kelvin, which was exactly as predicted by standard big-bang cosmology.

- In the standard big bang, the early universe is as bright as the Sun's interior everywhere and consists of a dense, hot gas of mostly ionized hydrogen. As the photons scatter off the electrons in this gas, they acquire a blackbody spectrum in thermal equilibrium with the gas and keep the universe bright.

- As the universe expands, it cools to 3000 kelvin after 380,000 years. The photons in the early universe no longer have the energy to keep the hydrogen ionized. Then, the electrons and the protons recombine into hydrogen atoms, and the electrons that have been keeping the photons basically bottled up are gone. Then, the universe goes dark, and photons stream through the gas.

- Since this so-called recombination epoch, the universe has expanded a factor of 1000 in size. Due to this huge expansion, the blackbody photons have been redshifted—their wavelengths stretched from the optical to the microwave. Thus, the observed microwave background we see today is a picture of the universe when it was 380,000 years old. We can't see beyond this ultimate background—we can't look back farther than this time—because at earlier times, the universe was opaquely bright.

- The goal of the COBE cosmic microwave background isotropy observations was to search for the small-scale density fluctuations in the 380,000-year-old universe that gave rise to the large-scale galaxy structures observed today. The entire sky was surveyed at high sensitivity and 7 degrees resolution in search of the corresponding spatial variations in the cosmic microwave background temperature. A key challenge in analyzing any such all-sky map is separating out the true background from foreground radiation sources.

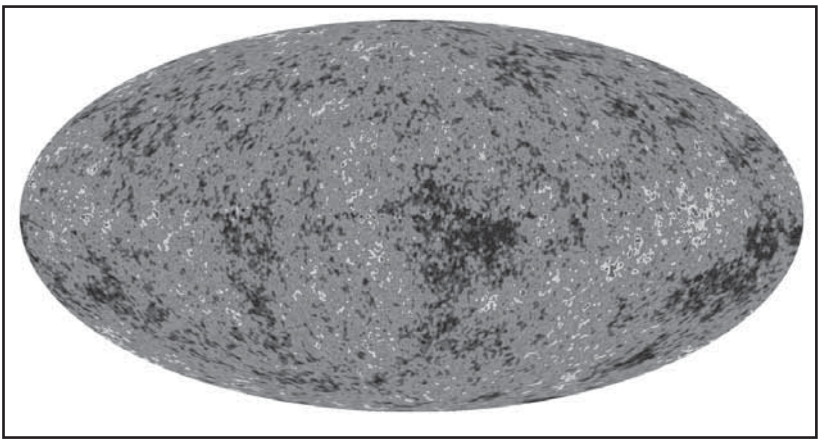
- For example, consider the DIRBE infrared sky map. In the case of the microwave background using the COBE DMR experiment, the cosmic microwave background radiation is completely isotropic, down to a sensitivity of just 0.2 percent. But as you increase the sensitivity higher, you see a dipole anisotropy, where anisotropy means that you see different temperatures in different directions. COBE was the first one to convincingly find small-scale variations in the temperature of the cosmic microwave background. In other words, it was the first clear detection of small-scale anisotropy in the cosmic microwave background.

WMAP and Planck

- The Wilkinson Microwave Anisotropy Probe (WMAP) space observatory was launched in 2001 to better measure and characterize the cosmic microwave background anisotropy at much smaller angular scales than COBE. The WMAP 10-arc-minute resolution is over 30 times higher than COBE. It collects microwaves with two 1.5-meter dishes. It orbits Earth from about 1.5 million kilometers away.

- With the map of the cosmic microwave background provided by WMAP, and then with other data showing how the universe has evolved over time in terms of galaxies, we can model what the cosmic microwave background should be, in terms of its tiny anisotropies, with the gravity and physics we know about. And the amazing thing is that we can reproduce the large-scale galaxy structure we see today evolving over time.

- Of course, there are still many questions remaining about this evolving universe. We still don't know what caused the big bang. What is the dark matter? We're still trying to figure that out. There



The cosmic microwave background reveals the slight patchiness coming from glowing sound waves that become, over time, galaxies and stars.

is a lot that we don't know, but the point is that the big picture seems to fit together.

- Because the seeds of today's universe are embedded in the cosmic microwave background, it continues to be a focus of detailed investigation. The very latest all-sky map of the cosmic microwave background just released is from the Planck Space Observatory. Based on Planck's first 15 months of data, this is the most sensitive map yet of the cosmic microwave background.

- Its angular resolution is 2.5 times that of WMAP. The science results in the first data release from Planck show a universe that's mostly consistent with what we've found from WMAP. Planck finds that the universe is about 13.8 billion years old instead of WMAP's 13.7. Planck also tells us close to what WMAP tells us—that the universe has about 5.5 times as much dark matter as the stuff we're made out of. The Planck map also shows us that the universe is indeed dominated by this thing called dark energy, which is causing an accelerated expansion of the universe.

- Over the ensuing years, Planck will continue to dig more and more cosmic clues from this cosmic microwave background radiation, which is so important because it unlocks all the secrets in the early universe. There is a lot more we can learn from this radiation.

Suggested Reading

Lemonick, *Echo of the Big Bang*.

Loeb, *How Did the First Stars and Galaxies Form?*

Singh, *Big Bang*.

Questions to Consider

1. Why isn't it possible to measure the isotropy of the cosmic microwave background radiation using the temperatures provided by cyanogen molecules in different sight lines through the galactic interstellar medium?

2. If cyanogen molecules could be detected in a spiral galaxy at a distance of 1 billion light-years, they should indicate a higher microwave background temperature than those in the Milky Way. Why?

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